GLOBAL WARMING AND WORLD ECOSYSTEM DISTRIBUTION: TOWARD QUANTIFYING ECOSYSTEM CHANGE

by

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Global Warming and World Ecosystem Distribution: Toward Quantifying Ecosystem Change

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Abstract

There is growing scientific consensus that the projected increase in atmospheric greenhouse gas concentrations will cause changes in the earth's weather patterns, such as increases in temperature and precipitation. In an attempt to explore the impacts of such change, researchers have quantified impacts in economic terms. However there are other effects that are not amenable to economic quantification. Because they are difficult to quantify, these non-market effects are difficult to include, and thus are often neglected, in the policy debate. One such effect is the impact of climate change on ecosystem characteristics and distribution.

This thesis seeks to find mechanisms to quantify ecosystem change. It builds upon a regional ecological model, the Holdridge Life Zone Classification System, which correlates vegetation type with parameters of temperature and precipitation. The Holdridge system has previously been used to produce maps which project biome distribution under current climate and atmospheres with double CO2 concentrations. These maps indicated significant change in biome distribution under potential climate change. In this thesis we assign carbon storage values to Holdridge life-zones and measure the changes in potential carbon storage under four climate model projections for North America and the globe. A "life-zone displacement" value is also introduced to allow for comparisons of the projections of biome change for each of the four climate models.

Regional ecosystem models such as Holdridge are equilibrium models and therefore do not incorporate transient effects that will be important for future ecosystem change, such as the rates of climate change and species migration. Despite the limitations of these regional models, quantifying the content of their biome projection maps could serve a useful function for policy analysis. Results of this thesis indicate that quantification can highlight the differences between various climate models. Future application of such quantification factors or indices using a probabilistic analysis approach under a multitude of climate change scenarios could project a range of possible ecosystem change outcomes. In this way, quantification factors will provide a useful tool for projecting ecosystem change in the context of uncertainty.

Thesis Supervisor: Professor Henry Jacoby,
William F. Pounds Professor of Management

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Finally, I wish to sadly acknowledge the multitude of species that we lose to extinction by the hour, day, or week, depending on who's counting. In the words of John Cougar Mellencamp "forgive us for we know not what we do."

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1. Problem Statement

Although there is great uncertainty as to the likelihood and magnitude of global climate change, there is growing scientific consensus that the projected increase in atmospheric greenhouse gas concentrations will likely cause changes in the earth's weather patterns, such as possible increases in world temperatures and precipitation. Studies have been completed which attempt to predict the social and economic impacts of such a change on agriculture, forestry, water resources, and coastal areas susceptible to inundation from possible sea level rise. Most studies discuss change in a qualitative manner. Perhaps the most widely recognized reports are those of the Intergovernmental Panel on Climate Change (Tegart et al. 1990; Tegart et al. 1992) which, although they discuss a wide spectrum of potential effects of climate change do not quantify the impacts of such change.

In an attempt to discuss the possible costs or benefits of potential change, some authors have quantified impacts in economic terms. Such information can provide useful measures for comparison. For example the costs of building sea walls, importing sand to beaches, or restructuring water projects can be estimated. Changes in relative distribution and abundance of crops can be projected and assessed economically. Such costs can be compared with costs of curtailing activities which emit greenhouse gases. There remain, however, many non-market effects that are not amenable to economic quantification and because they are difficult to quantify, they are difficult to include in the policy debate. One area that can not be easily discussed in quantitative terms, yet is quite

important, is the impact of climate change upon ecosystem characteristics and distribution.

This thesis seeks to find mechanisms by which we can quantify ecosystem change. We will discuss models currently used by scientists to study ecosystem change in response to global warming. We will then explore the possibility of using these models to break down ecosystem change into quantification factors so that we can intelligently include such change in the climate change debate.

1.2. Background

Climate's influence upon ecosystem distribution has been studied for some time (Koppen 1936; Holdridge 1947). Most of these studies use an observational approach which correlates existing vegetation distribution patterns with regional attributes of climate and soil type. The alternative is a mechanistic approach which analyzes the mechanisms by which ecosystems and vegetation are established and then applies these requirements to the regional climatic attributes. In an attempt to more accurately predict the impacts that climate change will have on the distribution of ecosystems, and the impacts that ecosystem change will have upon climate, models are now being introduced which build upon these observational and mechanistic studies and which simulate the change in ecosystem distribution under various climate change scenarios.

Most of this work is focused upon the feedbacks between vegetation and climate as a way to improve the ability of general circulation models (GCMs) to simulate changes in greenhouse gas concentration. Although it is recognized that vegetation has an impact on the balance of greenhouse gases (GHGs) and that, as the vegetation on the earth's surface changes, so too will its effect on this

balance, most GCM's do not include such interaction in their simulations. Currently, most GCMs treat the surface of the earth as uniform and unchanging. The interactions between vegetation and the earth's atmosphere are limited to vegetation effects upon surface albedo and seasonal changes in water vapor concentration (Sokolov 1993). Current research on ecosystem change due to global warming therefore is primarily concerned with understanding these interactions with the focus of improving the GCM's. Little attention has been paid to the impacts of change in ecosystems on a level of societal welfare.

For example in June of 1992, 160 nations signed the Convention on Biodiversity in Rio de Janeiro, demonstrating the world's concern for the conservation of species. Many reports addressing potential climate change mention that we can expect species extinction as organisms with narrow climatic tolerances, unable to migrate with the rate of climate change, are faced with anthropogenic barriers or competition from resident species. Few reports go beyond this superficial mention of such occurrences, however, and as superficial mention does not lend itself to comparison of impacts, it is difficult to include these concerns in the policy making process.

The following chapters will explore the question of how climate change may effect the distribution of natural ecosystems[1] with a focus on strategies that may enable quantification of the effects of such change. It is hoped that this effort will help to integrate ecosystem change into the policy debate. Our emphasis is on exploring the use of indicators which could potentially be used to

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[1] We will refer to ecosystems here in the same way that Atkin refers to natural vegetation. Acknowledging that this term could have many meanings we will "restrict its use to that of wild vegetation that is indigenous to an area. It is that which probably would re-occupy an area if conscious human intervention ceased to shape the vegetation cover." In this way the definition would not classify corn in the midwest US as natural vegetation, the definition could however include the savannas of Africa which perhaps have been shaped by years of human interaction (Atkin 1990, pg. 43).

compare the impacts of climate change on ecosystems. Such a quantification is difficult but its difficulty should not preclude attempt. As ecologists are uncomfortable with making broad-based generalizations and policy makers have few indicators with which to carry on discussion, the effects of climate change upon ecosystems has been largely ignored.

1.3 Structure and Focus of the Thesis

This thesis will begin with a discussion of past ecosystem responses to changing climate. It will then examine the types of ecosystem models used by ecologists to explore the mechanisms by which ecosystems are created and the effects that stress may have upon them; the focus will be on a specific sector of models; the regional and global correlational models. A description of these models will illustrate their relative strengths and weaknesses. The next chapter will focus upon uncertainty, mechanisms that have been used to address it, and the difficulty of incorporating uncertainty into ecosystem change analysis. We will then present a discussion of how ecosystem change could be quantified using two quantification functions as examples; changes in biomass, and "life-zone displacement." These two functions will be used to compare a projection of current ecosystem distribution with projections of double CO2 atmospheric concentration futures using four different GCM projections for North America and the globe. For biomass quantification we find that while all GCM scenarios reveal a potential net increase in biomass, there are great discrepancies between them in their projections on the level of individual biomes. The life zone displacement values prove to be useful in comparing the various scenarios and demonstrate potential for utilizing this quantification factor to convey uncertainty in modeling ecosystem responses to global warming.

This study is a component of a project being conducted at MIT under the Joint Program for the Science and Policy of Global Change. The intent of the program is to take an integrative approach to the problem of climate change. The issue of climatic change has stimulated a great deal of study and research. Thus far, such research has focused primarily upon the impacts of climate change on individual sectors, often conducted in great detail (for example, agricultural impacts, sea level rise, energy use). Based upon our limited ability to model and forecast climate change, such detail is arguably inappropriate. Rather than concentrating on detailed study of individual sectors, the focus of the Joint Program is to study interactions between the impacted sectors.

For example, scientists may predict a decrease in productivity of a major crop for a certain country, an apparent negative impact of climate change. However, the overall welfare of that country is not determined by the production of a single crop. It will depend on which crops it can still produce, the effect of climate change on the crop productivity in other countries, and the price of the commodities that perhaps it can now more readily produce. On the other hand, an increase in crop productivity of one country may be met by an even greater increase in another country resulting in a dilution of the world market and a decline in the welfare of both countries. The focus of the integrative approach is to examine such interactions and their mutual feedbacks.

Of course the various interactions can be quite complex and it is not possible to model the entire earth. However, it is important to understand these interactions and to incorporate them into the study, and modeling of, the effects of potential climate change.

In short, current research is primarily concerned with a bottom up approach. If climate change occurs, impact X will occur in region Y. The focus of the integrative analysis of the Joint Program is to start from the top and work

down. In doing this we risk creating a gross schematic of the complex interactions of the globe. However, if we do not concentrate on the interactions between systems that are effected by climate change we are not getting the whole picture. We are seeing the trees but not the forest.

An example of both the limitation and usefulness of this approach is in the Joint Program's utilization of a 2-D GCM. In comparison to the models that are currently being used to forecast global change, the 2-D model is simple.[2] However the 3-D GCM, which is most often used to derive climate change scenarios requires several months to run whereas the 2-D model can be run in a matter of hours or days thus enabling modelers to change variables with relative ease and explore feedback effects.

As part of the Joint Program one of the goals in our treatment of ecosystems is to provide information that can be used as part of the overall integrative assessment. The models we will use are not comprehensive. The methods of quantification will be far from precise. The intent is to recognize that the living components of our planet will have an impact both on potential physical aspects of future climate change as well as the social welfare of the planet and that it may therefore be useful to discuss these impacts quantitatively.

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[2]The 2-D GCM assigns each latitudinal band a single value for temperature and precipitation based on the aggregate average over the entire latitudinal band.

Chapter 2

Biotic Response to Change

In this chapter we will examine some of the effects that a rapidly changing climate may have on ecosystems. We will discuss how ecosystems have responded to change in the past and the factors that may be important for their future response to climatic change. This chapter will serve as a background for understanding ecosystem models and their limitations which will be discussed in chapter three. Because plant species are stationary, it is expected that they will be more sensitive to climatic changes. Much of the following discussion therefore focuses on vegetation responses.

2.1. Previous Response to Change

Temperature changes that have taken place over the last two million years have been more significant than those expected to occur under potential anthropogenic climate change over the next 100 years. For example, the end of the last glacial period 10,000 - 15,000 years ago saw an increase in the mid-latitudes temperatures in eastern North America and Europe of 5° C. Adjustment to this change took place with little loss of species diversity (Solomon and Cramer 1993).

However, the speed of the warming events has been at the rate of 0.1-0.2° per century during these geologic time periods. This is in contrast to the rate of temperature change of even the more modest current scenarios which project a change 15-30 times greater at 3° per century. Latitudinal temperature gradients of 0.5° C/100km in summer and 1.5°/100 km in winter in mid latitude North America could induce summer isotherms to shift northward 120 - 150 km per

century and winter isotherms to shift northward 540 - 630 km per century (Solomon and Cramer 1993).

There have been five episodes of mass extinctions in our planet's history: the Ordovician, 440 million years ago; the Devonian 365 million years ago; the Permian, 245 million years ago; the Triassic, 210 million years ago and the Cretaceous, 66 million years ago (Wilson 1992). It is not clear what caused these extinctions, although the Cretaceous episode is thought to perhaps have been the result of a sudden alteration in climatic conditions, possibly from a meteor impact or a fantastic volcanic explosion (Wilson 1992). Other events may have been the result of plate tectonic migration and therefore an effective change in climatic conditions on the various continents as these contintents moved over or toward the south pole. These episodes saw varying amounts of species loss, the worst perhaps being that of the Permian which saw an approximately 54% loss of families and perhaps between 77 to 96% of all marine animal species (Raup 1991).

2.2. Migration Response to Rapid Warming

Seeds can be dispersed for tens and even hundreds of miles as they are carried by animals, wind, or water. If these seeds find conditions suitable for growth, they too will mature, produce seeds for dispersal, and therefore migrate in response to changing climatic conditions. Fossil pollen records indicate that species migrate at different rates (Davis, 1981). As a result, a new ecosystem that is produced will most likely be quite different from the one from which its constituents originated. The most opportunistic or fastest migrating species are first established and followed by competitors. Given enough time, this new system *may* resemble the older one as the ecosystem migrates or increases its

geographic range. Such so-called "ecosystem succession" requires long time periods, particularly among the slowest-growing species, forest trees.

The rate at which a variety of species of trees have migrated in the past has been measured primarily by analyzing the fossil pollen record. For example, the maximum rates of migration for animal-transported seeds in eastern North America have been calculated at 10 - 15 km per century and wind-transported species at 20 - 30 km per century (Solomon et. al., 1984). These derived rates match well with measured rates obtained by studying the fossil pollen record. The measured rates of Davis (1981) show rates of displacement of 10 - 35 km per century and 20 - 40 km per century respectively for the same or similar species. The difference between these measured migration rates and the possible movement of the isotherms just mentioned reveals a discrepancy which is a cause for concern to many ecologists.

Perhaps the record for the most rapid tree migration rates are those measured by Gear and Huntley (1991) for Scots pine of 35 - 80 km per century in northern Scotland in response to a rapid midpostglacial climate change. Even if this last example of Scots pine is seen as approaching the 120 to 630 km isotherm displacement rate mentioned above, it could be argued that this relatively fast rate will be optimistic in comparison to potential climate change in the 21st century. The rates mentioned above assume that barriers to seed transport do not exist and that sites for establishment of new trees are readily available. Another study by Davis et al. (1986) has shown that tree migration from the Lower to the Upper Peninsula of Michigan was delayed by as much as a thousand years because of the barrier presented by lakes Huron and Michigan, which narrowed to as little as 10 or 20 km at the Straits of Mackinac during the Nipissing Great Lakes stage, 4000- 6000 years ago (Larson 1987).

It must be emphasized that these migration rates occurred at a time when humans had relatively little impact on the earth's landscape. Today, migrating species will face anthropogenic barriers which they did not encounter under prehistorical conditions (Flather and Hoekstra, 1989). As much as 30% of the world's rainforests has been eliminated, most often in a fragmented fashion (WRI 1992). Costa Rica for example has lost approximately 70% of its forests to since 1940, making migration practically infeasible (EPA 1993). The grasslands of the US and other world temperate regions have predominately been transformed into agricultural regions presenting wide barriers to seed transport which contain few sites on which migrating species can become established. Faced with these barriers, it is highly questionable whether ecosystems will be able to migrate "intact." Additionally, it must be recognized that the population base for most species on earth has dwindled considerably as humans have an increasing degree of influence on the natural landscape. This too could have negative impacts on migration rates (Webb 1993).

Another area that will be quite sensitive to the rate of change will be that of life-cycle response. Many species of plants undergo life-cycle stages that may be disrupted under a rapid change of climate. Plants require a certain length of time to complete their life cycles with trees requiring many years. Life cycles consist of many stages. Conditions must first be conducive to the establishment of seedlings. Once seedlings are established they may grow to reproductive maturity. At this point they can produce healthy seeds which may then disperse and in turn become established as seedlings. Different environmental stages may require different environmental conditions. For example, seedlings of eastern hemlock require constant, but not excessive, soil moisture for many successive growing seasons. For mature trees of this species it is more important to have a high nutrient soil content rather than a constant soil moisture. If a species has

persisted in a particular area it is reasonable to assume that the requirements of its separate life stages are met by its immediate environment. Conditions necessary to complete one stage usually occur in the same places as conditions needed for other stages. However, under the relatively rapid movement of isotherms there is potential for an uncoupling of the necessary life-cycle stages. For example, if under climate change a stand of eastern-hemlock is subjected to fluctuations in soil moisture, the mature trees may be able to tolerate these new conditions with little problem. However the conditions of the area will no longer support eastern-hemlock seedling growth leaving the mature trees to die without replacement.

Another constraint is the intrinsic timing of the life-cycles of the tree species. Some species such as the fast growing jack pine may only take 5-10 years of growth before they can produce viable seedlings whereas other species such as the slower growing eastern hemlock may take 50 to 450 years before producing viable seedlings. The differences in the years required within a species is determined by the growing conditions. For example the eastern hemlock will require more time to mature if water and or nutrients are limited. Hemlocks also grow more slowly in the shade of the forest. They are, however, well suited in the long term to such conditions because they contain the moist soil that the tree requires (Solomon and Cramer 1993).

If change occurs rapidly, it could perhaps kill trees before they reach reproductive maturity. It is quite possible that in 50 to 100 years climate change could create conditions that are unsuitable for seedling growth and if seedlings do grow, they will perhaps not have enough time to reach reproductive maturity. If seeds require conditions of soil moisture but are distributed to an area where forests are suffering from dieback due to heat stress or water deficiency (such as

the lower region of the boreal zone) increased exposure to sunlight may decrease the soil moisture necessary for germination.

Such conditions will select for species that complete their life-cycles relatively quickly. Additionally, these opportunistic organisms will most likely be species which utilize the sun (increased in the form of closed canopy forest dieback) to reach reproductive maturity quickly. These primary successional species would potentially dominate. Such species contain less carbon and species diversity than older growth forests. (It has been estimated that terrestrial carbon storage of forests could be reduced by up to 50% in the short term under rapid climate change (Smith and Shugart 1993).) These effects will be compounded by other chronic secondary effects of climatic change such as increased pollution and acidification that is currently the cause of a great deal of forest loss in such areas as Germany and Norway. These secondary effects will additionally limit the ability of tree species to complete their lifecycles within the time frame required by rapid change.

2.3. CO2 Fertilization

Some argue that the above effects could be partially ameliorated by CO2 fertilization which could increase productivity and therefore enhance the ability of species to complete their life-cycles. Although this effect has been studied for crops and positive responses have been recorded, long term studies of perennial species and large scale systems have been limited and are thus far inconsequential (Körner 1993).

Chapter 3

Ecosystem models

3.1. Background

In order to understand the current distribution of ecosystems and the processes by which ecosystems are established, scientists have developed ecological models. Ecological models can be characterized as (from Joyce et al., 1990):

1) physiological-based plant models which measure the response of individual plants to changing conditions;

2) population models which examine plant establishment, growth, seed production and death;

3) ecosystem models which focus on biogeochemical processes of fixation, allocation, and decomposition of carbon, and the cycles of nitrogen, phosphorus, sulfur and other elements;

4) regional or global models which correlate vegetation distribution with climatic variables of temperature, precipitation (Smith et al., 1992) and soil type (Prentice et al., 1992).

There is a great deal of room for overlap in these models yet they remain surprisingly unique. Integration and aggregation of the models is still in the developmental stages, although there have been attempts to incorporate nutrient cycling of ecosystem models into gap-phase models of forests (Pastor and Post, 1988) (The gap phase model is a widely used type of population model which predicts the establishment, growth and death of species and accounts for competition for light, water, and nutrients (Botkin et al., 1972; Shugart, 1984)).

Also there is currently an effort to integrate biogeochemical models with regional models (Kittel, 1993; Baskin 1993).

Spatial dimensions of GCMs are coarse when compared with the dimensions of the range of ecosystems (Joyce et al., 1990). Models which combine the transient effects of atmospheric and ecological interaction are basically limited to biogeochemical models. These models focus upon the changes in nutrient cycles under changing climatic conditions. These models are useful in determining the health of an ecosystem undergoing environmental stress. They can give an indication of what may happen to productivity of a certain type of ecosystem, however they do not allow for a transition into a different ecosystem type but only the changes to the existing one. For example there is no allowance for in-migration of competitive species (Smith 1993; Baskin 1993).

Researchers concerned with the macro-effects of climate change upon ecosystems are basically limited to utilizing GCMs or fossil pollen records to project equilibrium conditions and existing ecological models are then applied to these conditions to determine species abundance and distribution. Although variations of the models mentioned above are applied in this fashion, perhaps the most useful models used to assess the gross effect of climate change upon ecosystems are the global and regional models.

3.2. Global and Regional Models

Three great patterns dominate the earth and are of tremendous importance to man-the pattern of climate, the pattern of vegetation, and the pattern of soils. When the three are laid on upon another, their boundaries coincide to a remarkable degree because climate is the fundamental dynamic force shaping the other two.
D. I. Blumstock and C. W. Thornthwaite (1941), "Climate and the World Pattern."

Since the time that Blumstock and Thornthwaite made the above statement, research on vegetation distribution and significant progress in soil science have demonstrated that the correlation is more complex than first thought. The correlation between vegetation, climate, and soils is certainly significant, but far from precise. Global and regional models, however, take advantage of this generalization to project global vegetation patterns.

Three such models will now be examined; the Holdridge Life-Zone Classification System, the Biome model, and the Mapped-Atmosphere-Plant-Soil System (MAPSS) model. Only one, the Holdridge model, will be used in the quantification exercises, however a discussion and comparison of the these three models will provide a background for understanding the underlying assumptions that are made in setting up regional models as well as the mechanisms which contribute to the determination of the distribution of terrestrial ecosystems.

3.3. The Holdridge Model

The model most often used to assess the impacts of climate change upon ecosystems is the Holdrige Life-Zone classification system (Holdridge 1947). The Holdridge system correlates climatic indices with 37 "life-zones" (alternatively, "eco-climate zones") ranging from polar desert to wet tropical rainforest (figure 3.1). Only two variables are used in determining classification, average biotemperature and average annual precipitation. The value of biotemperature is simply the averaged sum of all temperatures above which a plant is photosynthetically active (roughly taken to be above 0°C). To calculate biotemperature, the values of all temperatures below freezing are set to zero and the average of this adjusted sum is determined.

The Holdridge diagram is formed using two identical axes for average annual precipitation to make up two sides of an equilateral triangle (figure 3.1). The third side of the triangle is a logarithmic axis for potential evapotranspiration (PET) ratio, which is measured in millimeters per year (mm/yr). Axes for mean annual biotemperature are then set parallel to the base of the triangle.

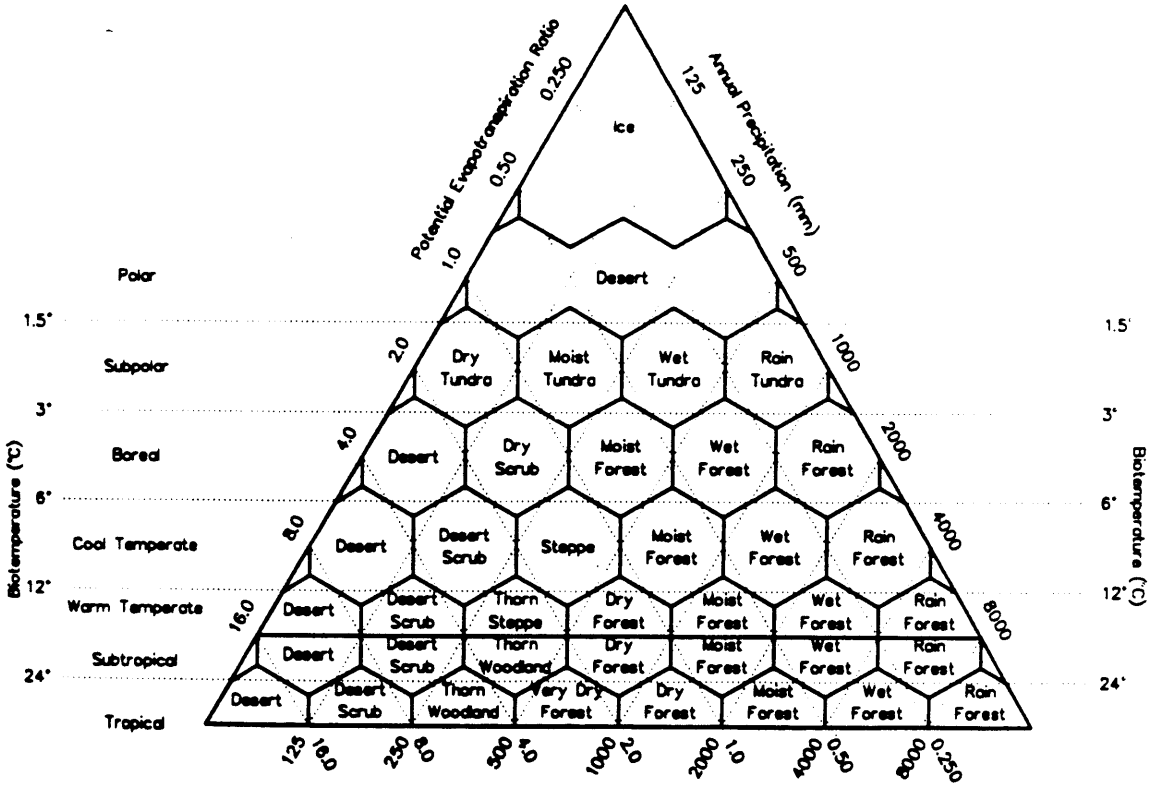
PET is basically an indication of humidity. Evapotranspiration refers to the transfer of water to the atmosphere from both evaporation of surface areas as well as water transferred via transpiration of plants. PET is then calculated as the amount of water released to the atmosphere under "natural conditions," i.e. when there is sufficient but not excessive water available throughout the growing season. The potential evapotranspiration ratio which makes up the third side of the triangle is the quotient of PET and average annual precipitation.

Based upon study of several ecosystems, Holdridge assumes that PET is proportional to biotemperature with a proportionality constant of 58.93, i.e.

Annual Potential Evapotransipiration (PET) = 58.93 X Annual Biotemperature

PET is therefore not an independent variable but simply derived from the two primary variables of precipitation and biotemperature.

Figure 3.1. The Holdridge Life Zone Classification System Triangle



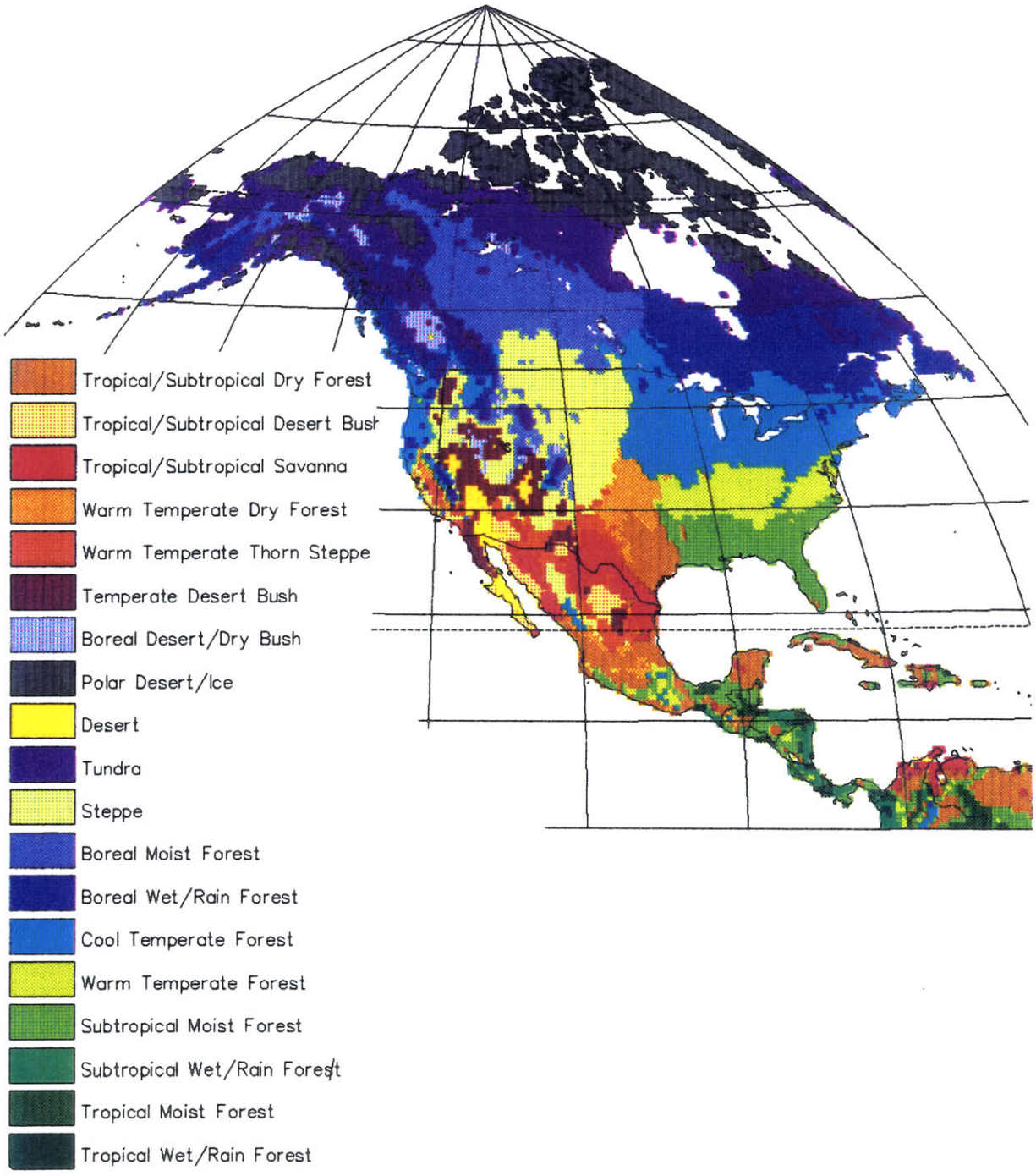
The additional axis placed between 12° and 24° which divides the warm temperate and the subtropical zones is a frost line. The exposure to frost being an important factor in determining vegetation distribution.

Emanuel et al., (1985b), Solomon and Sedjo (1989), Prentice and Fung (1990) and Smith et al., (1992) have utilized variations of the Holdridge Life Zone Classification System in order to simulate potential ecosystem distribution under climate change. The primary objective of the studies by Prentice and Fung and of Smith et al., were to assess the sensitivity of terrestrial carbon storage to climate change, i. e. whether, under climate change, terrestrial vegetation would act as a net source or sink of carbon. Each eco-climatic zone was assigned a level of carbon storage. These zones were then superimposed on a 2 X CO2 climate and the change in global vegetation distribution was estimated. Up to 50% of current world-wide eco-climate zones changed to a new eco-climate zone under a perturbed climate. These studies suggest that total vegetation would increase, acting as a net carbon sink. Samples of Holdridge Vegetation Map Projections are displayed in figures 3.2. Results are shown for current vegetation distribution and four GCM projections of 2XCO2 climate.

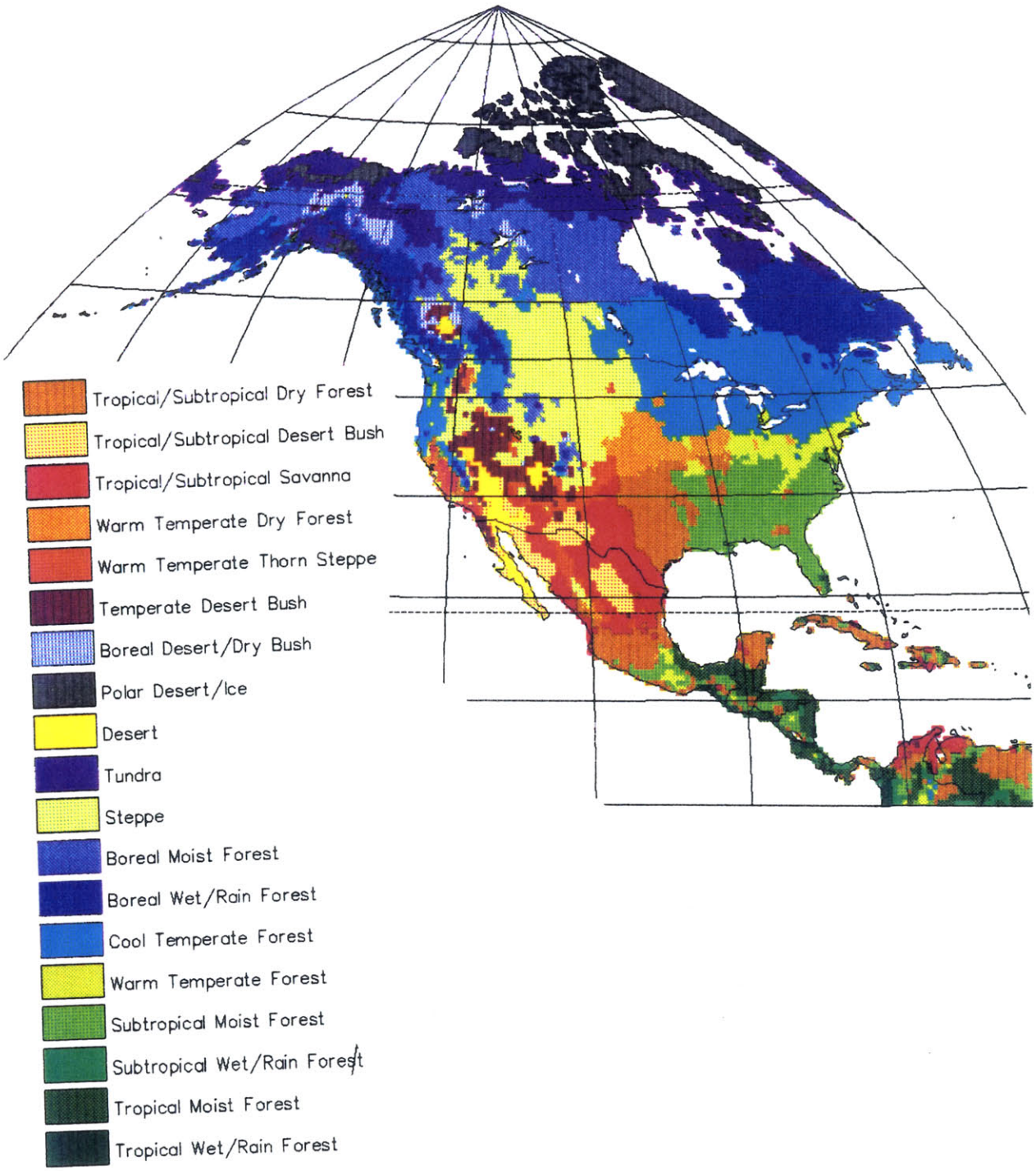
These studies are limited by their assumption that vegetation and climate are in equilibrium. When considering the previous ecosystem response to change discussed in the last chapter, this is a significant limitation. Studies by Solomon (1986), Neilson et al., (in press) and Smith and Shugart (1993) which consider problems of vegetation adjustment, indicate that although equilibrium projections show an increase in the carbon storage of a 2 X CO2 climate, change at the predicted rate could result in forest dieback and a net release of a significant amount CO2 in the immediate term. For their analysis, Smith and Shugart assume a step change in climate, obviously a gross simplification. They classify three processes for controlling changes in vegetation and associated soil

Figure 3.2. Holdridge Vegetation Maps for climate projections of a) current climate, and 2XCO2 projections of ; b) OSU, c) GISS, d) GFDL and e) UKMO. Maps and data were kindly provided by Thomas Smith of the University of Virginia.

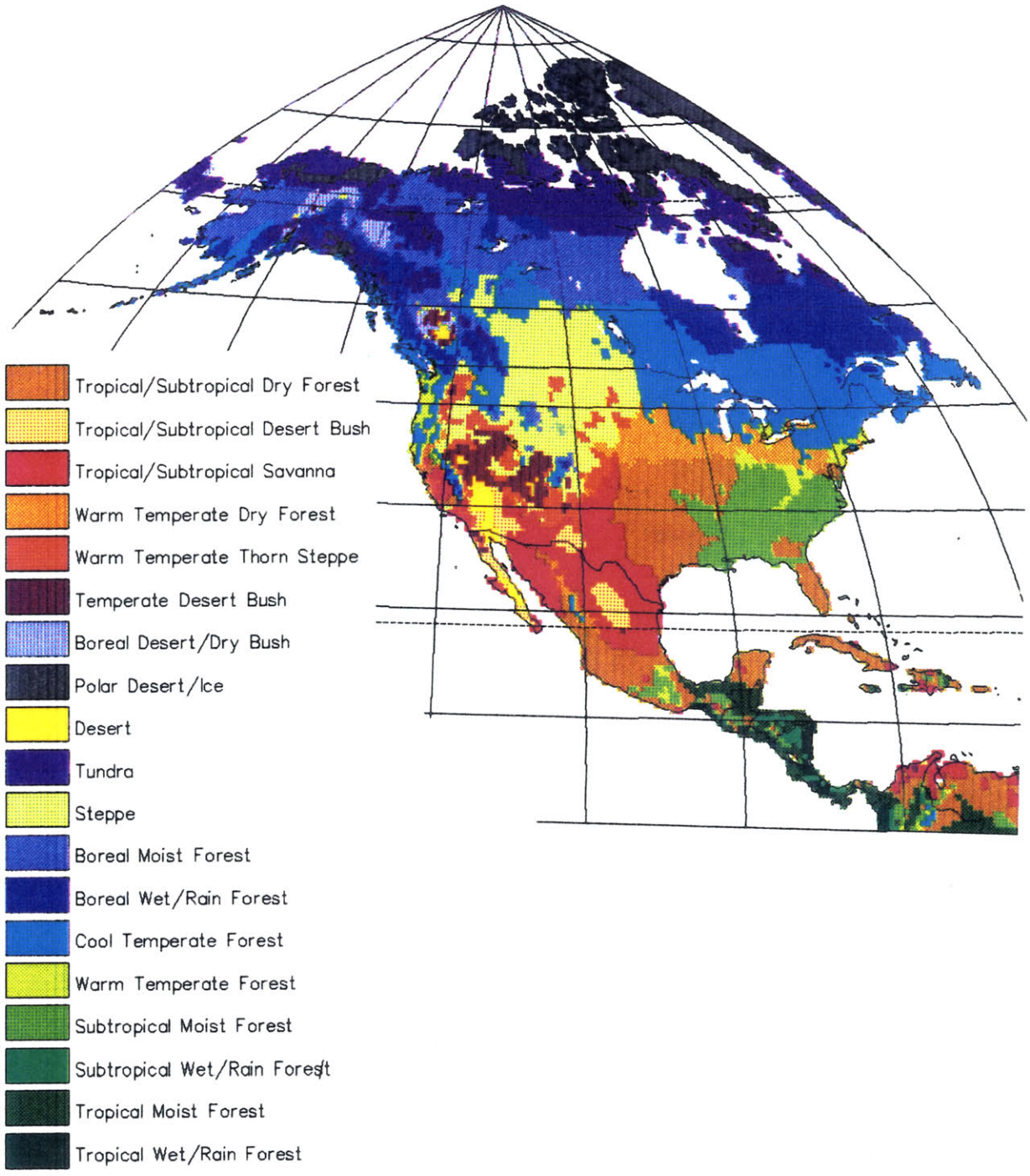
a) Current climate using IIASA data



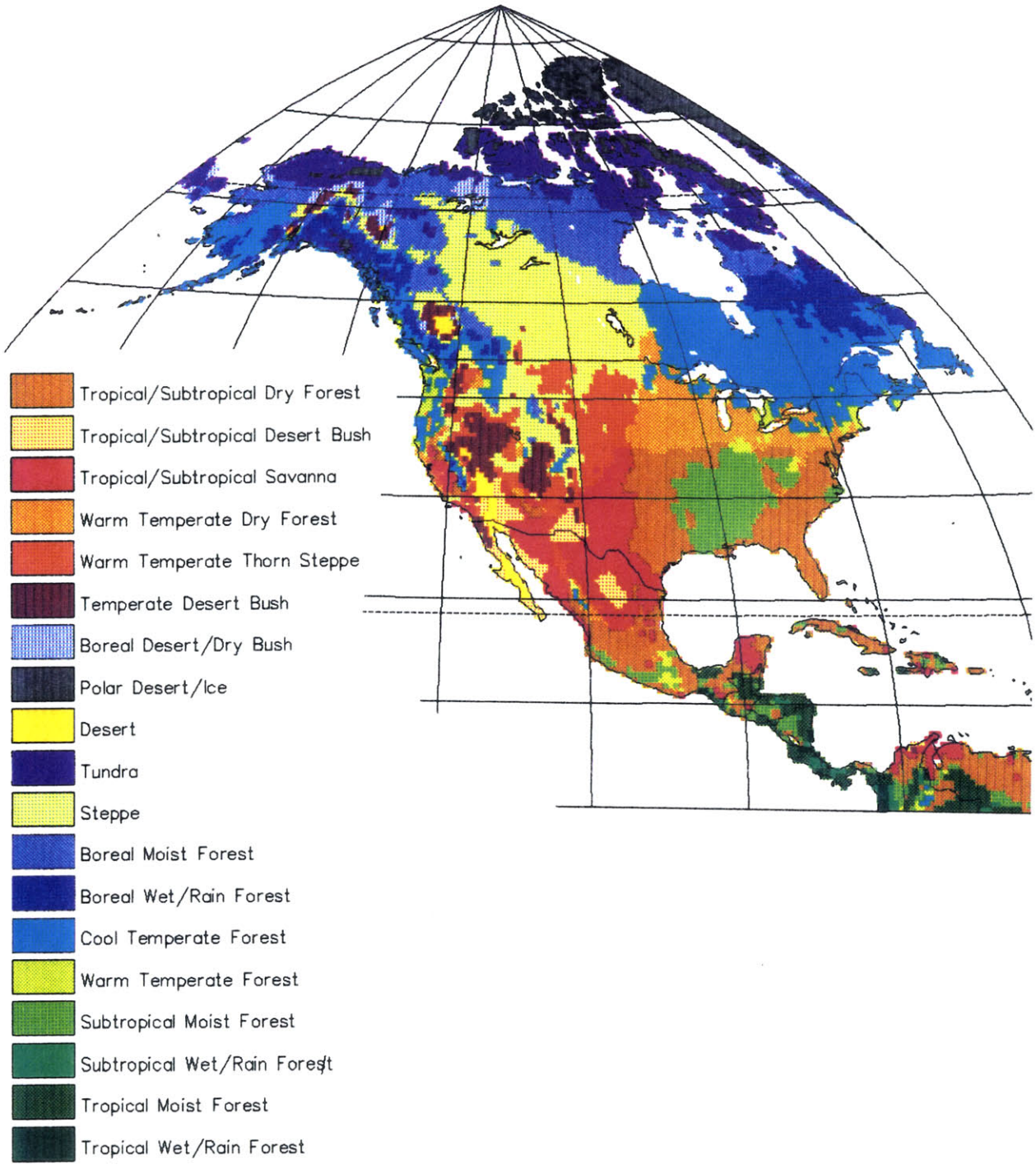
b) OSU double CO2 projection



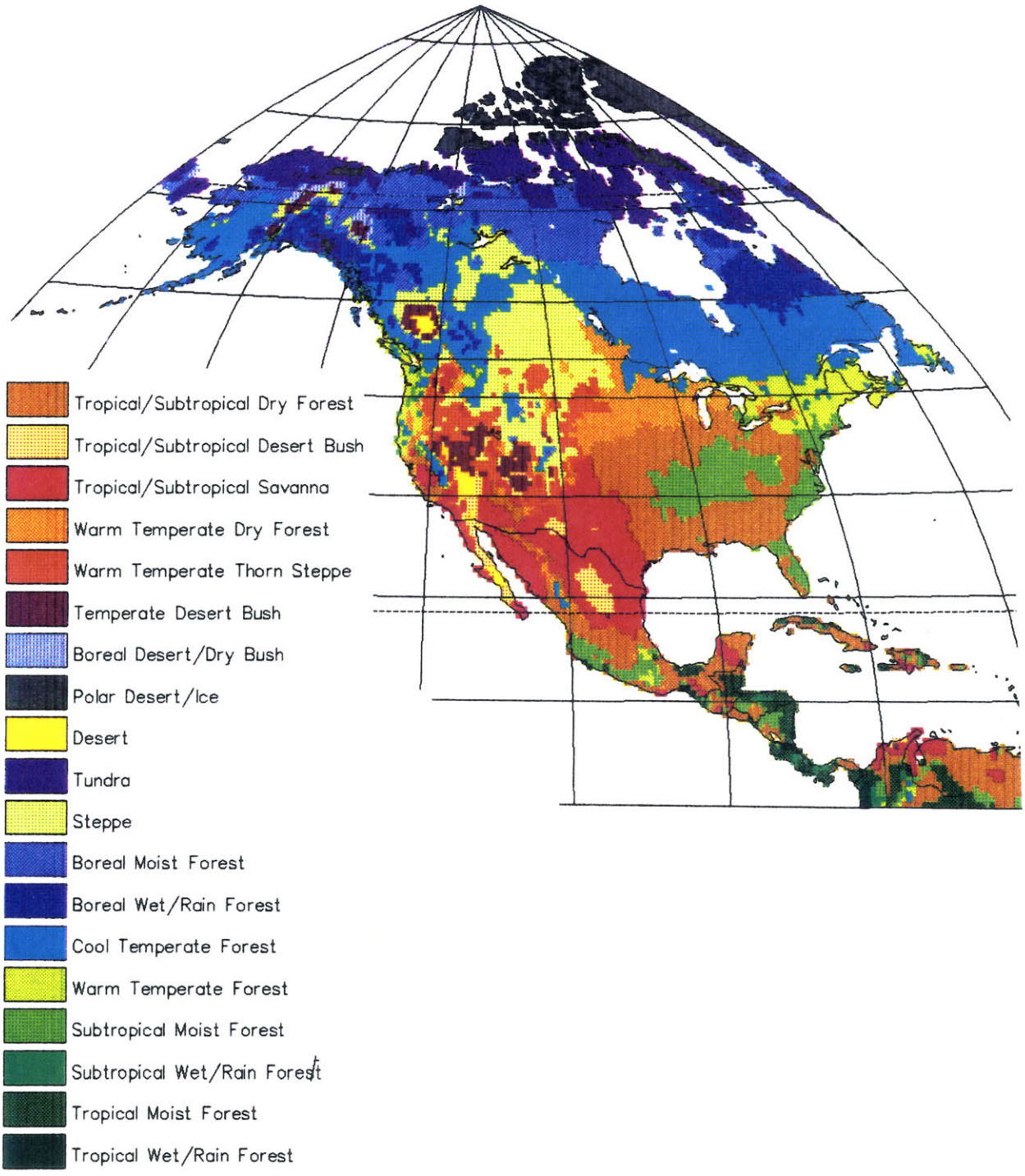
c) GISS double CO2 projection



d) GFDL double CO2 projection



e) UKMO double CO2 projection



carbon: "(1) dieback of existing vegetation as a result of increased aridity (accompanied by wildfire); (2) successional replacement of existing vegetation by vegetation predicted for that location under the new climate (natural mortality of the original vegetation followed by the establishment and growth of replacing vegetation); and (3) successional replacement limited by the need for immigration of new species." In their assessment, the establishment of successional vegetation under climate change does not offset the release of carbon that comes with mortality. "Changes in vegetation and soil type that result in a net release of CO2 to the atmosphere (such as those caused by wildfires) could be more rapid than changes that result in a net increase in terrestrial carbon storage (such as species immigration and soil formation), so that in its transient response to climate change, the terrestrial vegetation soil system could be a net source of carbon to the atmosphere." (Smith and Shugart 1993)

In an attempt "to address the potential impacts of climate change on forested systems at regional and global scales under an array of possible climate change scenarios" a comprehensive study has been done by EPA (1993). The study utilized the Holdridge Life Zone model to focus upon the impacts of climate change on the global distribution of two forest systems, boreal forests and tropical forests, "in order to represent contrasting cases of the interaction of human [i.e. anthropogenic barriers] and biological constraints on the potential response of forest ecosystems to climate change." In addition, case studies were utilized in order to provide a more comprehensive assessment of impacts at the regional level in an effort to include land use and transient effects which would facilitate a more detailed evaluation of potential impacts and adaptation strategies.

Similar to the studies mentioned above, results indicate that climate change could have a major impact on ecosystem distribution and composition. In a case study of Costa Rica, for example, a moderate climate change scenario (+2.5° C change and 10% precipitation increase) projected that 38% of the country's land area would change from one eco-climate zone to another. A more extreme scenario (+3.6 C and 10% precipitation increase) projected a 47% change. An increase in spatial resolution of the models increased the land area change to 43% and 60% respectively (Tosi et al., 1992). Overall, the study projects that the "ability to select suitable species for plantation forestry may enable the forestry and fuelwood sectors to offset potential declines in production of native forests, however, the impacts on naturally maintained forests and nature conservation could be severe."

3.4 The BIOME model

A recent model offered by Prentice et al. (1992) attempts to step beyond a simple correlational approach toward one that is more "mechanistic." Prentice et. al. set out to create a model where plant types are not taken as given but rather emerge out of mutual interactions (for example inter-species competition). The biome model is based on the premise that "models to predict the response of global vegetation patterns to climate change must start from the climatic tolerances of different types of plants rather than from the apparent climatic distributions of biomes as they exist today."

Perhaps the most comprehensive assessment of current global vegetation distribution is that of Olson et al.(1983). Which describes 101 functional plant types distributed world wide. It was the intent of Prentice et al. to utilize this data set to both calibrate their model and assess its ability to reproduce existing

vegetation distribution. To accomplish this they aimed to produce "the simplest possible model-that is, the smallest number of plant functional types, constraints and driving variables-to achieve [the] goal of simulating the broad features of present vegetation as indicated in the data of Olson et al.."

The biome model is based upon fourteen plant functional types (table 3.1). These functional types are derived from three primary and two subsidiary driving variables, and thirty-two constraints. The characteristics of regional climate and soil type are put through this "environmental sieve" to yield a description of biome type (table 3.2). The variables and constraints are described below.

Cold Tolerance.

Plants have somewhat distinct degrees of cold tolerance based upon the mechanisms utilized to resist cold stress. For example woody plants of the tropics generally do not survive temperatures below zero. Other plants such as broad- leafed evergreens can survive an occasional frost but will generally not be found in areas where the temperatures reach -15°C. Broad leaf deciduous trees of the temperate regions shed their leaves in the winter and can survive by utilizing a supercooling mechanism up to the point at which water spontaneously nucleates and freezes at -40°C. The general limitations of cold tolerance are summarized in table 3.3 (from Woodward 1987).

Table 3.1. List of Biome types for the BIOME model (as taken from Prentice et al 1992)

Combinations of dominant plant types that occurred in the global model application, and the names they were given for mapping

Plant types	Biome name
Tropical evergreen =	Tropical rain forest
Tropical evergreen +	
Tropical raingreen =	Tropical seasonal forest
Tropical raingreen =	Tropical dry forest/savanna
Warm-temperate evergreen =	Broad-leaved evergreen/warm mixed forest
Temperate summergreen +	
Cool-temperate conifer +	
Boreal summergreen =	Temperate deciduous forest
Temperate summergreen +	
Cool-temperate conifer +	
Boreal evergreen conifer +	
Boreal summergreen =	Cool mixed forest
Cool-temperate conifer +	
Boreal evergreen conifer +	
Boreal summergreen =	Cool conifer forest
Boreal evergreen conifer +	
Boreal summergreen =	Taiga
Cool-temperate conifer +	
Boreal summergreen =	Cold mixed forest
Boreal summergreen =	Cold deciduous forest
Sclerophyll/succulent =	Xerophytic woods/scrub
Warm grass/shrub =	Warm grass/shrub
Cool grass/shrub +	
Cold grass/shrub =	Cool grass/shrub
Cold grass/shrub =	Tundra
Hot desert shrub =	Hot desert
Cool desert shrub =	Semidesert
Dummy type =	Ice/polar desert

Table 3.2. Environmental Seive (as taken from Prentice et al. 1992)

Environmental constraints (mean temperature of the coldest month, T_c; growing degree-days on 5°C base, GDD; growing degree-days on 0°C base, GDD_0; mean temperature of the warmest month, T_w; Priestley–Taylor coefficient of annual moisture availability, (α) and dominance class (D) for each plant type in the model*

	T_c		GDD	GDD_0	T_w	α		
	min	max	min	min	min	min	max	D
Trees								
tropical evergreen	15.5					0.80		1
tropical raingreen	15.5					0.45	0.95	1
warm-temperate evergreen	5					0.65		2
temperate summergreen	−15	15.5	1200			0.65		3
cool-temperate conifer	−19	5	900			0.65		3
boreal evergreen conifer	−35	−2	350			0.75		3
boreal summergreen		5	350			0.65		3
Non-trees								
sclerophyll/succulent	5					0.28		4
warm grass/shrub					22	0.18		5
cool grass/shrub			500			0.33		6
cold grass/shrub				100		0.33		6
hot desert shrub					22			7
cold desert shrub				100				8

*An additional 'dummy type' is defined for computational consistency. This type has dominance class 9 and no environmental limits, representing the 'plant type' that would occur under conditions unfavourable for any other type (e.g. ice caps).

Table 3.3. Minimum Cold Tolerances for Selected Plant Types (Woodward 1987))

Broad-leaved raingreen	0 to 10
Broad-leaved evergreen (frost-sensitive)	0
Broad-leaved evergreen (frost-resistant)	-15
Broad-leaved summergreen	-40
Broad-leaved summergreen (e.g. *Betula, Populus* spp)	No limit
Needle-leaved evergreen (e.g. *Agathis, Araucaria*)	-15
Needle-leaved evergreen (temperate taxa)	-45
Needle-leaved evergreen (boreal taxa)	-60
Needle-leaved summergreen (e.g. *Larix*)	No limit

Because temperature extremes were not available at the level necessary for their analysis Prentice et al. utilized a regression equation (derived by Muler (1982) from data of 2000 world-wide weather stations) based on mean monthly temperature:

$T_{min} = 0.006T_c^2 + 1.316T_c - 21.9$

where T_{min} = minimum temperature, and T_c = mean temperature of coldest month.

Growing degree-days (GDD).

The concept of Growing degree-days is similar to the Holdridge concept of biotemperature, that is, that species require a certain number of days above a minimum temperature for proper growth and maintenance. As can be seen in the table 3.2, GDD is assumed not to be a constraint for those species with mean monthly temperature minimums above 5°C such as the tropical rainforest (i.e., these species are not limited by GDD). For plants of tundra and cold deserts which require only very short growing seasons the minimum temperature for calculating growing degree-days is the summation of days above 0°C. Growing

degree-days for the other plant functional types must be above 5°C (see Table 3.2).

Chilling requirements.

In addition, many species, particularly those of the temperate regions such as deciduous trees, require time periods below a certain temperature. For example, temperate deciduous species do not grow in botanical gardens of the tropics because they require winter temperatures below freezing to ensure proper bud burst in the spring. Other species in table 3.2 which have a value for T_C max have similar requirements.

Soil moisture.

Whereas moisture is represented in the Holdrige system as average annual precipitation with the PET derived from a relationship between values of precipitation and temperature. The Biome model attempts to incorporate soil type and factors of seasonality into the moisture variable of vegetation distribution.

How precipitation is distributed over seasons as well as texture and depth of soil layers contributes significantly to the type of vegetation that an area can support. For example a region with a Mediterranean climate may receive a significant amount of rainfall in the winter months, however as much of it will be lost as runoff it will be unavailable for plant use in the summer months. Similarly the texture of the soil may be a significant factor in determining the amount of water that a plant can utilize. For example a deep layer of loamy soil may have the capacity to carry winter moisture into the season of summer water stress while a shallow, sandy, or clay soil will have limited water holding

capacity. Again these two areas may have the similar values for average annual precipitation yet support quite different plant types.

The biome model utilizes a scalar, "alpha", based on the seasonal course of soil moisture with water use treated as independent of vegetation cover. "Alpha" is the Priestley-Taylor coefficient, or ratio of actual evapotranspiration (the emperically based measure of the actual total of both evaporation from the ground area plus transpiration from vegetation) to equilibrium evaportranspiration assessed over the full year (Hare 1980). It can be considered as an integrated measure of the annual amount of growth-limiting drought stress on plants.

The soil is treated as a single moisture store whose size is a characteristic of the soil. "Alpha" is calculated from an algorithm which is based on site latitude, soil water-storage capacity and monthly means or totals of temperature, precipitation and sunshine (the amount of sunshine is based upon an inverse measure of cloudiness).

After the "environmental sieve" is applied to yield the *potential* plant functional types, a dominance hierarchy is applied to yield the final proposed biome type. If two potential plant functional types have the same dominance "value." They are considered to make up their own particular biome (table 3.1). The dominance hierarchy "is an admittedly artificial device, whose main purpose is to facilitate comparison with global vegetation classifications such as that of Olson et al. (1983)." It is therefore not intended to determine the distribution of plant species at the individual level but to give a flavor of the character of a biome based upon the dominant constituents.

The biome model has been applied to data of current climate and yields a fair comparison with the map of Olson. This is not surprising however as the Olson map was used to derive variables that were put into the model and at this

stage in its development the emphasis of the model was to predict the current natural vegetation described by Olson et al.. In light of this fact it is questionable just how much more mechanistic the model is than the Holdridge Life-Zone classification system.

3.5 Mapped-Atmosphere-Plant-Soil System (MAPSS)

3.5.1. Discussion of MAPSS

As stated earlier, the major problem with these models is that they assume a steady state and can not simulate the mechanistic transition of biomes from one type to another. The Biome model described above is arguably an improvement over the Holdridge classification scheme because it makes some allowance for soil type and seasonality of precipitation. Nielson et al. (1992) set out to establish a even more "mechanistic approach to biome modeling, one that can be incrementally developed to incorporate transient behavior, ecosystem productivity, trace gas emissions and disturbance regimes (e.g. wildfire)."

Like the Holdridge and Biome models, this model is constructed under the premise that climate is the principle determinant of vegetation distribution, however it attempts to incorporate other factors deemed important in determining the final characteristics of the biome. Although the MAPSS model utilizes more parameters in determining eco-climate zones, current versions still fall short of the proposed goal of incorporating transient interactions of vegetation and climatic feedback. Although the approach could perhaps be classified as more mechanistic than the previous two models, it too is calibrated with the very climatic input that it attempts to simulate as output. Additionally, as with the other models, its present approach is still limited to steady state.

Nielson et al. (1992) indicate that systems like Holdridge show as much as 50% to 90% spatial displacement of extratropical biomes. The authors emphasize that such a shift will not be spontaneous. The "mechanism for spatial shift could be dominated by either 1) competitive displacement of northern biomes by southern biomes (referring to the Northern Hemisphere), or 2) drought-induced dieback of areas susceptible to change. The current suite of global biosphere models cannot distinguish between these two processes." They set out then to develop a "rule-based, mechanistic model" of regional biomes. "The model is based on a suite of empirically generated conceptual models of biome distribution based on the regional water balance and the potential supply of water to vegetation from two different soil layers, surface for grasses and deep for woody vegetation." The moisture available to these two layers is determined by the seasonality of the water supply, i.e. whether the area receives precipitation during the spring and summer growing season or in the winter (when growth is constrained by both sunlight and temperature).

Neilson et al. (1989, 1992) developed the model from transect analysis of over 1200 weather stations in the conterminous U.S. (figure 3.3) and over 7,000 USGS gaging stations. They utilized this data to relate "the seasonality of temperature, precipitation and runoff patterns to physiological requirements of plants during different parts of their life-cycles and seasonal cycles" (Neilson et al. 1989).

The model is based on a detailed set of rules of vegetation moisture and energy requirements. For an example of these rules we provide a decision tree based upon the MAPSS model as it was applied to the continental US in figure 3.4. A full description of MAPSS is not appropriate here, instead we will highlight a few of the rules of the model below.

Figure 3.3. Distribution of Stations for MAPSS Input Data (Neilson et al. 1992)

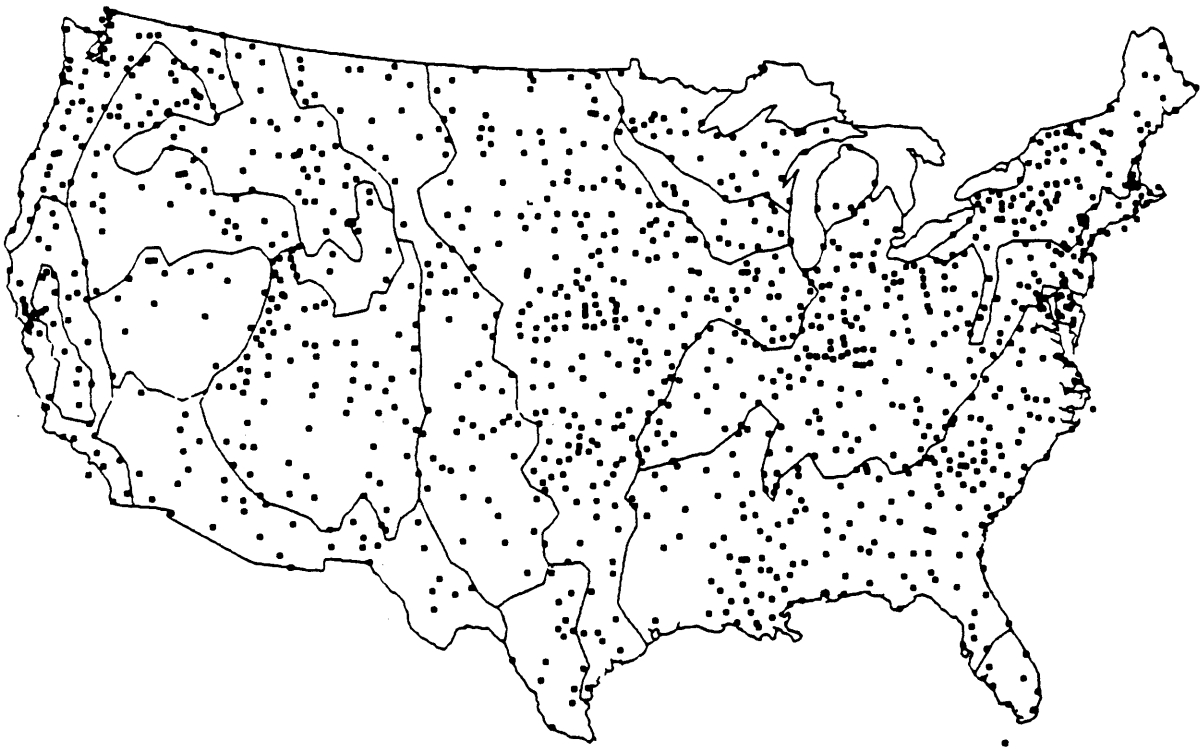
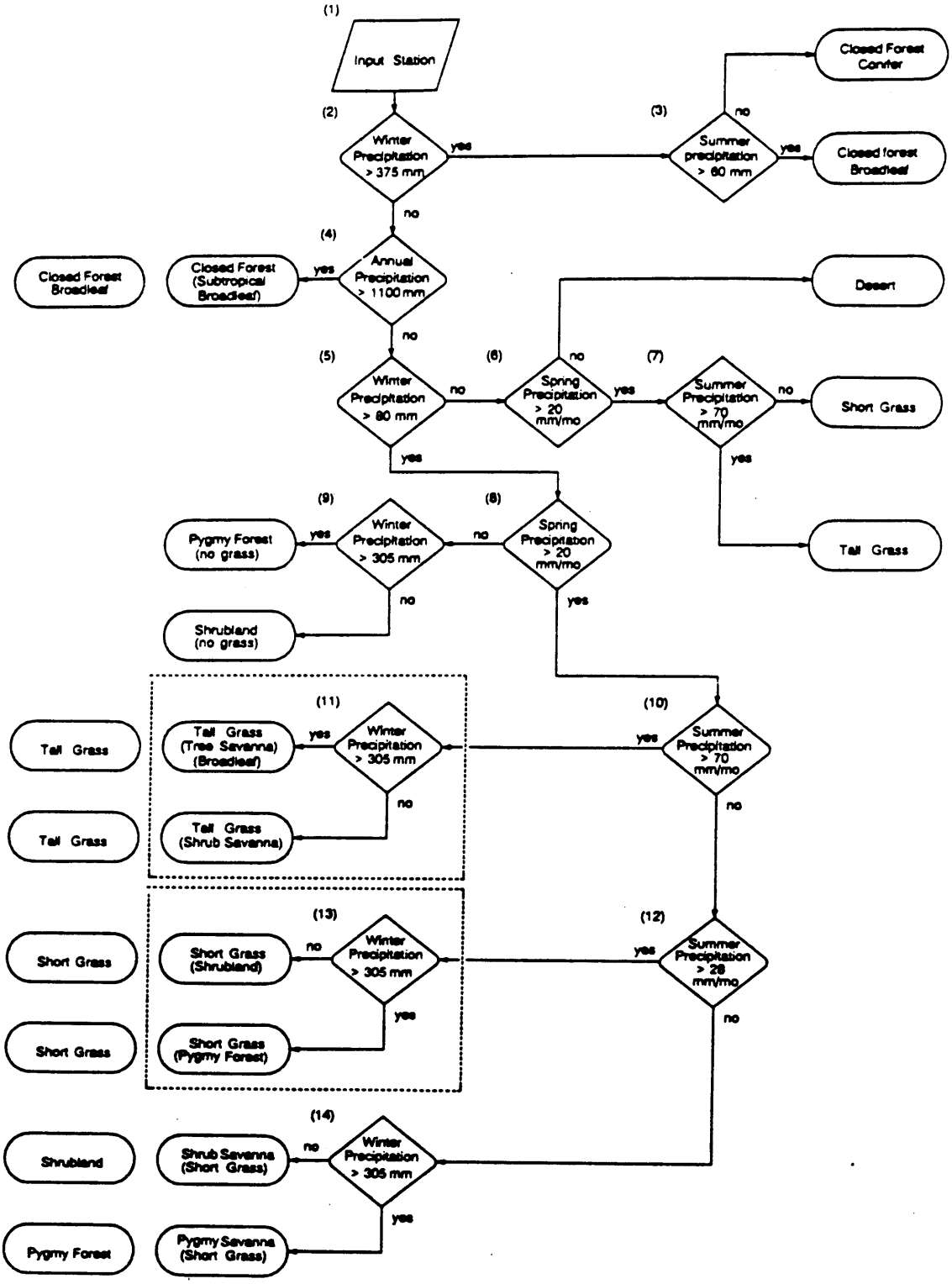


Figure 3.4. Decision Tree for MAPSS Model for the Continental US (Neilson et al. 1992)



3.5.2.. Structure of the Model

Leaf Area Index

The fundamental assumption of MAPSS is that vegetation leaf area will find a maximum that just utilizes available soil moisture. If there is a higher leaf area, rates of transpiration will increase, deplete the soil moisture and yield a negative feedback for leaf growth. Likewise, a low leaf area will result in an excess of soil moisture which over the years will likely be utilized to increase the leaf area until a threshold for drought is reached. The predicted leaf area in MAPSS is relative to the projected vegetative ground cover area and is termed the leaf area index (LAI).

LAI is an ambiguous term. Leaf area is important because it is through the leaf surface that moisture is lost. The level of moisture released from the plant to the atmosphere is determined by the stomates; guard cells on the surface of the leaf. If stomates were universally found on the top of the leaf, it would be relatively straight forward to determine the leaf area that is susceptible to water loss. However, many species have stomates on both sides of their leaves or surrounding them in the case of needle-leafed species. There is a great deal of error in calculating a general value for LAI on a per biome basis. This is particularly difficult for biomes with canopies of widely mixed species type. Another limitation of note is that LAI is determined to be constant throughout the growing season, beginning at first frost and ending with the last.

Closed vs. Open Canopy

As stated earlier woody vegetation requires deep soil moisture, grasses require moisture at the surface during the spring and summer. A mixture of woody and grass species can occur if there is sufficient moisture at each level and

if the existence of one species does not preclude the other, i.e. the canopy of a woody biome must allow enough light to the surface if the biome is to support grasses as well. This type of open canopy implies that there is a sufficiently low level of deep soil moisture to not support a closed canopy forest. If "spring rains are accompanied by high mid-summer rains, surface soil will remain moist and a large grassland should be supported, e.g., the Tall Grass Prairie. If both winters and springs are quite dry, maintenance of either woody vegetation or grasses is hindered and a desert may be expected" (Neilson 1992).

Woody Species vs. Grasses

In general, woody species such as trees are prone to grow in environments that have deep soil moisture. If an area receives a great deal of moisture in summer and spring, seasonal grasses will quickly deplete the soil of its moisture and allow little to seep into the lower layer. If the area receives a good deal of moisture in the winter, when grasses do not grow, the moisture will seep into the lower layer where it would be available to the deep roots of the woody species. Therefore an area that primarily receives rain in the summer will support tall grasses (the mid-western prairies of the US), an area which receives rain in the winter will primarily support woody species (the chaparral of California), an area that receives rain at both times will support both types of species.

Calculation of the competition between woody vegetation and grasses entails the competition for light and water. A simulation of this competition is based on first calculating the LAI of the woody species based on water balance. The potential grass LAI is then based on the amount of light left-over for growth of grasses. Based on the grass LAI, the water balance will change as the grasses utilize soil moisture. This will negatively impact the availability of water for the

woody species. These two steps are iterated until a simultaneous solution for light and water competitions is reached.

Temperature Constraints

Not all biomes are restricted by water balance some are related to temperature constraints. Two good examples are the boundary of the temperate forest with the boreal forest (Burke et al. 1976, Arris and Eagleson 1991) and the boundary between the Southeast pines and hardwoods with the oak hickory forest to the north (Neilson et al. 1989). The model imposes an absolute temperature contraint for these species.

A "unique feature of the model is the temperature-based definition of seasons." Winter begins (and later ends) when mean monthly temperature drops below 14°C. Likewise the beginning and ending of summer occur at 18°C. The temperature threshold is set at this level because it corresponds to the point at which precipitation cannot infiltrate the deep soil layer.

Evergreen vs. Deciduous Forests

There are two rules that determine the state of evergreen or deciduous forest. The first test is for minimum winter temperatures that fall below -40° C (the supercooled freezing of water) at which point deciduous species can not grow. A regression analysis yields that this temperature is represented by a mean monthly temperature of 16°C.

A second rule based on summer moisture separates the temperature deciduous trees or shrubs from coniferous of other microphyllous (small or needle leafed as opposed to broad leafed) species. If summer precipitation is low (representing low humidity) than the vapor pressure gradient is high, favoring a microphyllous species. This distinction does well at segregating the coniferous

forests in the Northwest and the microphyllous shrubs in the interior West from the broad-leafed species that predominate east of the Rockies, isolating the dry summers of the western US.

The southern part of the US also supports evergreen species. A third evergreen rule is used to distinguish the areas which rely on mild winter temperature. This requires a more rigorous parameterization as the effect of the native deciduous trees on the water balance are not considered.

Fire

Fire is added to the model based upon the amount of summer rainfall and biomass. I.e. if summer rain falls below a certain amount and a threshold of biomass is present, fire is assumed to occur. The woody species are removed from this area and the LAI of a grassland is re-calculated without competition from the woody species. This scheme does a good job at separating the Great Plains grasslands from the Great Basin shrub-savanna.

3.6. Limitations of the Models

A major flaw with the models just discussed is that they do not incorporate any of the barriers to change that were discussed in chapter two. In their current state, these models are crude assessments of equilibrium conditions (although the goal of MAPSS is to allow for an integration of transient effects.) As static models, it is recognized and emphasized by all who study and use them that they are by no means forecasts of future ecosystem distribution. However from the vegetation maps projected by these models (such as the Holdridge maps shown in figure 3.2) an uninformed analyst may draw the conclusiuon that, as climate changes, ecosystems will merely migrate intact with changing climate.

The areas which show no change in biome or life zone under climate change will remain as they are and that we will see changes only in the regions which showed a biome change.

This will certainly not be the case. It is possible that up to 90% of community formations will see significant change. (Neilson, in press) It has been proposed that the transition zones between ecosystems or biomes, termed ecotones, will be the most heavily impacted areas under climate change and that changes at these ecotones could serve as indicators of changing climate. This may be true, however, changes will very likely occur at the core of the biome as well and could be severe. Neilson points out that at the ecotone there is a great deal of diversity and therefore species that could perhaps survive on either side of the ecotone. (Neilson, in press) As climate changes, those species best suited will simply become dominant. However, in the core of the biome where there is relatively less species diversity. If the few present species are unable to respond to climate change there is a chance for large scale dieback. For example, if an area becomes subject to drought stress but at a gradual level, then perhaps the plants will simply respond by decreasing their leaf size. If however change is rapid, and the species effected are slow growth species, drought stress could result in the loss of a great number of organisms as they are all competing for drastically reduced soil moisture. (Neilson, in press)

The effects of climate change on ecosystems will certainly be more complex than simply a shift of existing ecosystems. In fact, we know from fossil pollen records that a temperate deciduous forest that exists today, although very similar in large scale biological interactions, is made up of quite a different mix of individuals than this same "ecosystem" a few thousand years ago. Organisms will react to climate change as individual species, not as communities. It is

important to recognize this and to acknowledge the uncertainty inherent in making interpretations about ecosystem change.

To demonstrate some of the uncertainties of the effects of climate change on ecosystems and the inability of the equilibrium models to measure them, we will examine one particularly controversial area, species diversity.

3.6.1. An Attempt to Measure the Impacts of Climate Change on Species Diversity

Rigorous indices which associate relative species diversity with ecosystem type do not exist. Few attempts have been made to quantify the amount of species or diversity loss that would accompany global climate change. One study by Leemans and Cramer (1993) makes a crude assessment of the impact that climate change will have upon species diversity by utilizing a species index compiled by Box (1981). Box assigns relative numbers of plant species to plant functional groups (table 3.4). Cramer and Leemans then assign these counts to Holdridge life zones. By comparing the change in area of the various Life Zones

Table 3.4. Box Correlations of Plant Diversity with Ecoclimatic Regions (Box 1981)

Region (1)	No. of life forms (2)	Main growth forms (3)
Tropics (excluding alpine)	18	trees, rosette-trees, etc.
Tropical alpine	2	tuft-treelet, small herb
Subtropical (including arid and mediterranean)	20	shrubs, succulents, rosettes, etc.
Tropical and temperate (mild winters, mainly S. Hem.)	10	trees, rosette-trees, ferns, cushions, etc.
Temperate zone	25	trees, shrubs, grasses, forbs, etc.
Boreal/temperate montane	3	needle-trees, krummholz
Temperate and polar/alpine	3	dwarf-shrub, herbs
Polar/temperate alpine	2	dwarf-shrub, small herb
Global	3	thallophytes, bunch-grass

The regions were determined by the ranges of the life forms involved. Each life form in Table 2 (including sub-types) was assigned to a single region of which it is most characteristic. The number of life forms assigned to each region is shown in column 2, and the most common growth forms in column 3. The greater diversity in the temperate zone probably reflects the greater diversity of temperate ecoclimates combined with the greater dominance by tree forms in the tropics.

between current and 2XCO2 projections they illustrate that there will be a net decline in the number of plant species and most likely other species as well. If an area changes from a life zone of a lower diversity index to one of a higher diversity index then it is proposed to result in no change in species diversity. An area that goes from higher to lower value is seen as losing species diversity.

The creation of new species is a process that takes place on a geological time scale. The creation of new species is not likely to be induced by the potential changing climatic conditions of the next 100 years or so. Therefore, a change in area from a life zone type of a higher diversity index to a lower index is perhaps best represented as a loss in the number of species, while a change in area from a lower to higher index would represent no change. Simply put, if a scrub area is

transformed into a desert, it will support no more species then the desert would normally be expected to hold.

According to Cramer and Leemans the change of an area to a higher index will actually not result in an increase in species diversity because "some species may not establish in areas with now-suitable climate because they may not reach them fast enough .... predictions derived from static models should therefore be more realistic for declining natural vegetation than for scenarios of species invading new areas" (Cramer and Leemans 1993).

Cramer and Leemans are certainly correct that many species will have trouble migrating and that climate change will most likely result in a *global* loss of biodiversity; however, the diversity in a specific area can certainly increase. Some species will certainly migrate. A human inhabitant of a polar desert (if there is one) will perhaps have the opportunity to see a greater number of species if this desert is transformed into tundra. The area of scrub that takes on the characteristics of a hot desert however, will see the expansion (migration) of desert species into the region. Those species which can not tolerate the new environment will most likely slowly migrate out or perhaps perish. An inhabitant of this area will have the opportunity to see a fewer number of *species.*

There are many problems with trying to quantify the impact that climate change will have upon species diversity. There is a great deal of uncertainty about what mechanisms create diversity. There is also disagreement over what species diversity really means.

3.6.2. Mechanisms Which Create Species Diversity

Six possible mechanisms for creating diversity (as described by Iwasa et al. for tree species) are described below.

1) Specialization of resource use. A community will have a greater number of species if they are "more specialized in a narrow range of the resources spectrum." A stable environment such as a tropical region will enable an organism to become adapted to specific stable conditions, whereas a region that sees great fluctuations, such as a temperate region will favor a species that can occupy a greater niche space.

2) Mode of disturbance. Random disturbances will maintain a certain level of species diversity as individual species are not able to become dominant.

3) Smaller opportunity for competition. Soil fertility and species richness are negatively correlated. This may help to explain the observed increase of species from the pole to the equator. For example, in the constant environment of tropical rain forests, most nutrient resources are likely to be captured by trees and the availability of nutrients in the soil is therefore low (Odum 1969). In contrast, in seasonal environments, the availability of nutrient resources in soil may have a seasonal peak. For example the defoliation of trees or a snow thawing eutrophic environment provides an opportunity for a few fast-growing species to dominate the community.

4) Productivity. Recent studies have correlated species diversity with annual actual evapotranspiration (Adams and Woodward 1989). However, "at this moment no convincing theory is available that explains why species diversity should be higher in productive habitats." (Schulze and Mooney 1993).

5) Specific herbivores and pathogens. If a plant which is dominant in a particular area acts as a host for a pathogen or is the favorite of a certain herbivore it can be open to a great deal of exploitation. This situation favors a diverse community which is relatively immune to such an occurrence. If pathogens and herbivores are for some reason dominant toward the equatorial regions this could be another explanation for the latitudinal diversity gradient.

6) Evolutionary/Ecological History. The fact that regions of extreme latitude have low tree diversity has been attributed to advances and retreats of glaciers over relatively short time periods. The climate of the ice ages also effectively fragmented habitat in the tropical regions. This may have provided a mechanism for increased speciation.

All of the above possibilities seem plausible and there is certainly room for overlap of the different mechanisms. For whatever reason, there is a rough trend of increasing speciation from the poles to the equator.

3.6.3. Measuring Diversity at the Regional Level

One well studied explanation for regional diversity is the theory of island biogeography proposed by Wilson and MacArthur (1967) who suggested that the number of species increases with an increase in area of their habitat. Their model was based on an observation that there is a consistent relation between the area of islands and the number of species that they maintain. For example, Cuba has many more species of birds, reptiles, plants etc. than Jamaica, which in turn has more still than Antigua (Wilson 1992). They found the relationship to hold throughout the globe and proposed that the relationship followed a simple arithmetic rule. The number of species approximately doubles with every tenfold increase in area.

The relationship is represented by the equation $S = CA^z$, where A is the area of the island, S is the number of species, C is a constant and z is a second constant that depends upon the type of species considered (i.e. birds, mammals, etc.) and the distance between the island and the mainland. The value of z is a parameter that is geographically specific. A value of z for birds of the Hawaiian islands may be different than a value of z for grasses in Indonesia. The range of

values for z throughout the world ranges from about 0.15 to 0.35 (Wilson 1992). By saying that the number of species doubles with a tenfold increase in areal size we take z to be $\log_{10}$ of 2 or z = 0.30. It must be emphasized that this is a very rough rule of thumb.

The concept of island biogeography is usually applied simply to islands surrounded by water. But the authors propose that other areas, for example, fragmented parcels of woodland or Amazonian rainforest (figure 3.5) could follow the same rules. Of relevance here is that climatic change could effectively reduce the areas of the fragmented parcels that are increasingly becoming the only areas where natural diversity is conserved. This could happen either from actual dieback of vegetation dominants or alternatively, by reducing the size of the core of the biome, i.e. an organism may be dependent upon a certain community of species. If climate changes the nature of the community to the extent that it will no longer support that organism its size is effectively reduced.

Figure 3.5. Reduction and fragmentation of the woodland in a) Cadiz Towhship, Wisconsin 1831-1950 and b) Costa Rica 1940-1987 (From Wilson and MacArthur 196; EPA 1993)

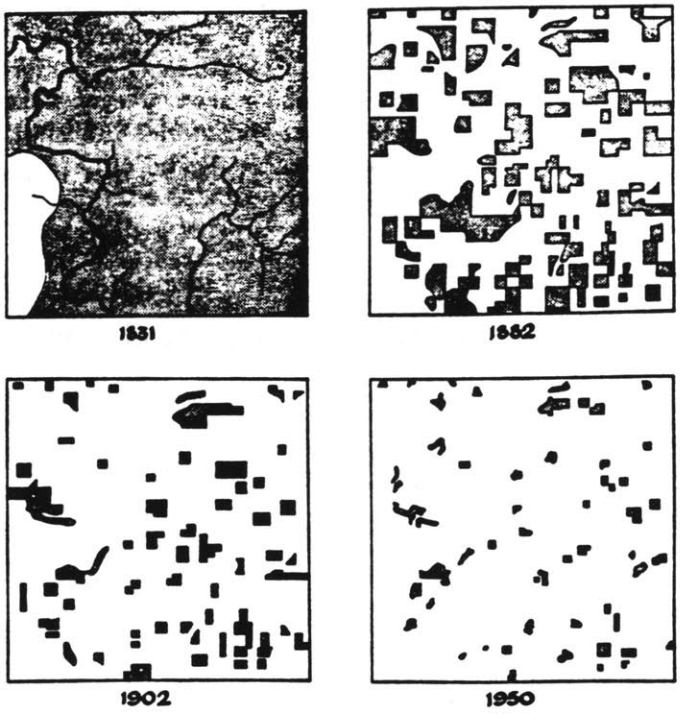
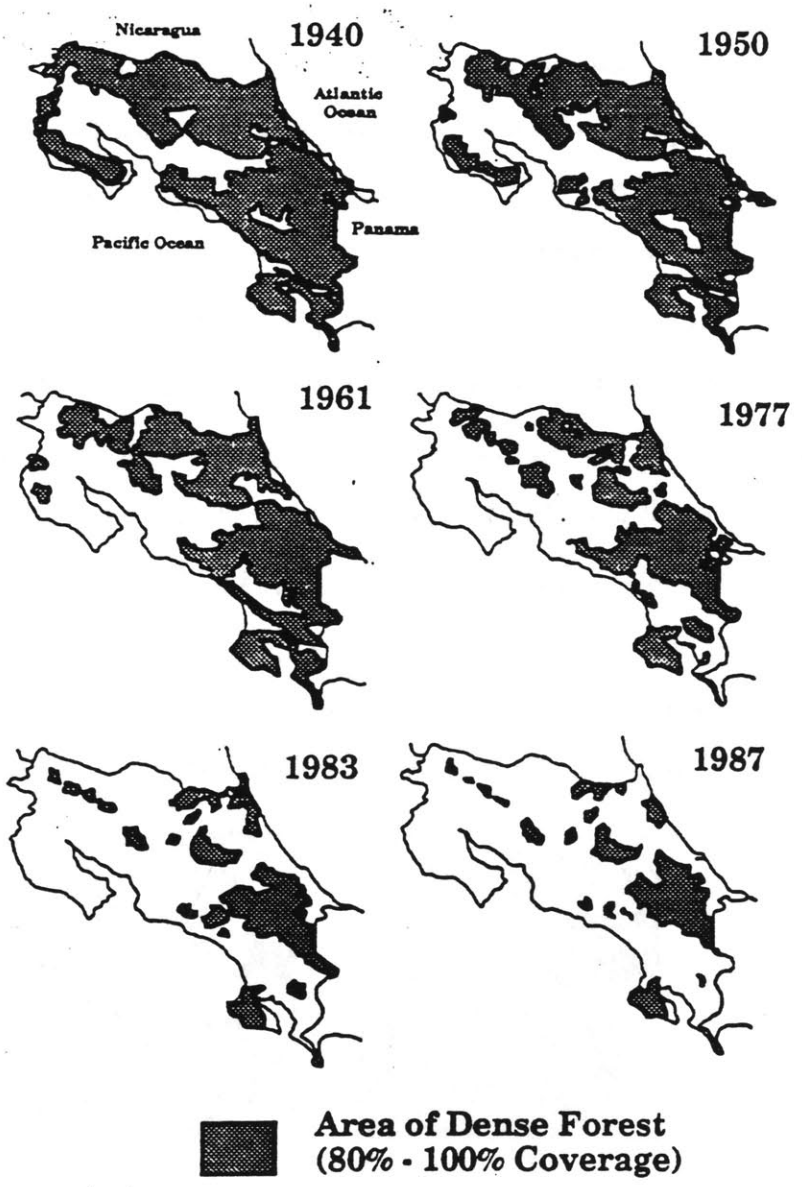


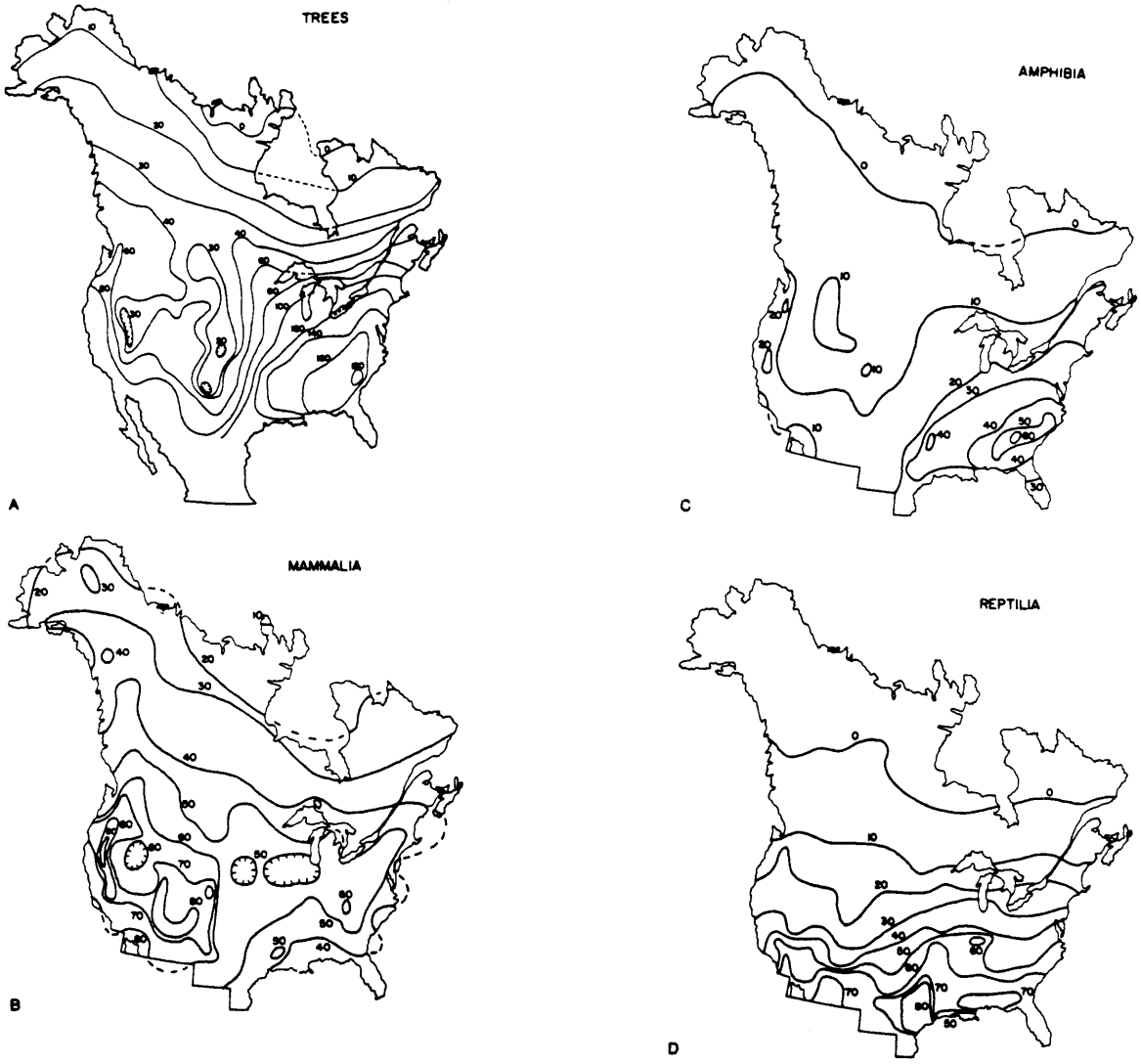
Figure 3.5 (cont.) b) Reduction and fragmentation of Forest in Costa Rica 1940-1987 (EPA 1993)



Only a few empirical trends have been established which try to correlate diversity with geographic area at the regional level. One by Woodward (1987) correlates plant diversity with minimum temperature. Another by Runke shows a gradient along latitudes by a decrease in soil moisture or the length of the cold or dry season (Runkle 1989). Botonists at The Nature Conservancy are working on a data base for empirical relations of species to region for North America. A correlation with regional maps produced from the models just described may therefore be potentially feasible (Morse and Maddox 1990).

One of the few studies done on the regional distribution of species diversity was by Currie and Paquin (1991) who created species contours for plants, birds, mammals, reptiles and amphibians in North America (figure 3.6). Currie and Paquin (1987) demonstrate that for plants, diversity depends on the amount of actual evapotranspiration (AET) (basically a measure of both moisture and solar radiation). This is not surprising as it is reasonable to assume that a greater amount of moisture will support a greater variety of plants. However, diversity for the other species in the study was dependent on PET (basically a measure of solar radiation). They reason that higher environmental energy in the form of solar radiation will require organisms to use less metabolic energy. Homeotherms (warm blooded organisms, such as mammals) will spend less energy maintaining their relatively warm body temperature. Ectotherms (cold blooded organisms, such as reptiles) will require less energy for metabolic processes in warmer regions. Species diversity, the authors conclude, is maintained on a regional basis by the amount of energy available to species. To account for the correlation described by the theory of island biogeography, they indicate that species diversity is limited on an island because there is simply less area on the island to receive solar energy.

Figure 3.6. Species Diversity Contour Maps (Currie 1991)



Species richness in Canada and the United States: A) (upper left), of trees; B) (lower left), of mammals; C) (upper right), of amphibians; D) (lower right), of reptiles. Contours connect points with the same approximate number of species per quadrat.

If the amount of energy were the only basis for species diversity than it could be argued that increased temperatures due to potential global warming will increase the level of energy available to all species. This generalization can certainly not be made. Under a rate of change that perhaps the planet has never seen, we can expect to lose a great number of species. For the reasons illustrated in chapter two; limited migration rates, life cycle constraints and lower population base; combined with habitat fragmentation touched upon in this chapter, the amount of species loss will most likely be great.

It is clear that regional models as they exist have little capacity to effectively model the impacts of climate change on species diversity. In the future, perhaps such a strategy could be envisioned building upon the work of Currie and his relations of species diversity to PET and AET. However, any strategy which realistically attempts to address the impacts of climate change on species diversity to incorporate the sensitivity of organisms to the rate of change. For now, regional ecosystem models could be useful in isolating areas that may be subject to the greatest change. Each of these areas, and their relative abilities to tolerate change, should be assessed and an aggregate assessment could perhaps build from there.

Chapter 4

Uncertainty

This chapter will illustrate some of the uncertainties inherent in the climate change issue. We will discuss how these uncertainties are often neglected and describe a few techniques that have been used to deal with uncertainty. We will then discuss the difficulties of incorporating uncertainty into ecosystem modeling in the context of climate change. This discussion will set the stage for chapter 5 where we will offer a strategy to address these difficulties

4.1. Scientific Uncertainty

4.1.2. Background on Modeling GHG Effects

The first quantitative assessment of the potential impact that increasing atmospheric CO2 concentrations could have on global temperatures was made by Swedish scientist Svante Arrhenius in 1896 (from Cline 1992). He calculated that a doubling of CO2 would cause a rise of 4°C to 6°C in surface temperature, not far from contemporary high end estimates (Cline 1992).

The simplest contemporary assessments of modeling potential climate change start with the global radiation budget. Radiative forcing, the term given for the value of solar radiation, at the top of the atmosphere (TOA) is estimated to be 340Wm^{-2} (Watts per square meter) of incident solar radiation on a global annual average. 100Wm^{-2} is reflected back out to space and 240 Wm^{-2} is therefore absorbed by the earth/atmosphere system. If the concentration of CO2 is doubled, this raises the atmospheric radiative forcing by 4 Wm^{-2}. On an energy

balance this translates into a 1.2°C increase. The real level of increase will depend, not solely upon the increase in radiative forcing, but will be subject to climatic feedback mechanisms as well. Principal feedbacks include the effects of:

water vapor- increasing temperature increases the atmosphere's capacity to hold water vapor. Water vapor is a greenhouse gas trapping more heat. This results in a positive feedback increasing temperature by a factor of approximately 1.6.

snow and ice albedo- snow and ice enhance the capacity of the earth's surface to dissipate heat by reflecting solar radiation. A warmer earth may have less snowpack and therefore less capacity to reflect radiation.

cloud feedback- cloud feedback could be either positive or negative. Clouds both reflect incoming solar radiation back out to space and trap long wave radiation that may dissipate out of the atmosphere. The net direction of this feedback is uncertain.

4.1.3. General Circulation Models and Climate Models

The large scale dynamics of the General Circulation Models (GCMs) are based on laws of physics. However small scale processes such as cloud feedbacks and deep ocean mixing must be simulated by using simplified physical terms called parameterizations. Two types of GCMs are used in climate modeling: atmospheric GCMs and oceanic GCMs. When either of these atmospheric and oceanic GCMs are run separately, they indefinitely reproduce reasonable equilibrium scenarios of atmospheric and oceanic processes respectively.

Contemporary climate models link together these two types of complex GCMs. When these models are coupled, they diverge far from equilibrium conditions. As a coupled model that diverges from equilibrium under unperturbed conditions is not a useful tool to forecast a change in current conditions, the interactions between the atmospheric and oceanic components of the climate models must be fixed. We are then forced to simplify the interaction between the atmosphere and ocean as static for the course of the model simulation (Stone 1993).

To verify climate models, historical data are used as input variables in an attempt to reproduce current climatic conditions. When this is done, the model produces a climate that, although reasonable, is quite different from the current climate. Sea surface temperatures, for example, have been off by as much as 6°C (Stone 1992). Modelers are then forced to "adjust for errors in the control run to provide a more realistic basic state for sensitivity experiments" (Houghton et al. 1990). Such techniques are called "flux adjustments" (Manabe and Souffer 1980) or "flux corrections" (Sausen et al. 1988). Like the parameterizations, these inputs are fixed and the same values are used for both the control and perturbed climate runs.

The basic problem with the GCMs is their inability to accurately calculate the contributions of physical processes that, although important, take place on a smaller scale than model resolution. Cloud feedback is one such factor. Other problem variables are those of moist convection, which effects water vapor's strength as a greenhouse gas and also cools the earth's surface; surface hydrological processes and their atmospheric interactions; and the interactions of terrestrial vegetation with the atmosphere.

4.1.4. Cloud Feedback

The area of perhaps the greatest uncertainty is the effect of cloud feedbacks that must be parameterized for incorporation into the GCM. As illustrated earlier, cloud feedback can potentially be either positive or negative. (Most GCMs incorporate it as a positive feedback). The extent of cloud feedback depends upon three main variables:

cloud amount- if cloud cover decreases, then the amount of solar radiation capable of reaching the earth's surface will increase as less is reflected upon entry resulting in a positive feedback. However, fewer clouds will absorb less long wave radiation reflected from the earth's surface. We could therefore see a net negative feedback.

cloud height- if clouds are displaced into higher colder regions, this could act as a negative feedback. Colder clouds emit less heat radiation allowing more to be trapped in the atmosphere.

cloud water content- an increase in the water content of the clouds could make them brighter and changes their emissivity. It is not clear whether the net feedback in this case is positive or negative (Houghton et al. 1990).

In an effort to investigate the causes of the varied results produced from contemporary GCMs, Cess et al. (1989) investigated the effects of changing sea surface temperatures on 14 atmospheric GCMs. In their analysis, the GCMs showed excellent agreement in clear sky sensitivity (i.e. under a simulation void of clouds). The conclusion was that most of the disagreement between these models was attributed to differences in the simulation of cloud feedback. The researchers determined a nearly threefold variation in climate sensitivity as produced by the models when incorporating cloud feedback; their values ranging from modest negative to strong positive feedback (Cess et al. 1989).

Despite these weaknesses, the IPCC scientific assessment states that the GCMs are "the most highly predictive tool we have to forecast future climate" (Houghton et al. 1990).

Not all climate researchers have as much faith in the GCMs. Stone and Risbey (1990) point out that the models do a very poor job at simulating a transfer of meridional heat flux (horizontal heat transfer between GCM grids). Here the results of the various GCMs differ by up to a factor of two (Stone and Risbey 1990).

They also state that "if the dynamical transports are sensitive to the sub-grid scale processes, then their changes are also likely to be biased by poor representations of the sub-grid scale processes. We therefore doubt that the GCMs currently in use for climate change experiments are better at simulating global scale climate feedbacks and temperature changes than simpler models that do not simulate large-scale processes from first principles."

Stone and Risbey touch here upon a very important limitation in utilizing the output of GCM simulations as input for regional ecosystem models; their inability to resolve sub-grid scale processes.

4.2. Grid Size

As can be inferred from the above analysis, the purpose of the GCMs and the simpler models is to forecast change on a broad scale. The grid size of the GCMs varies but are usually on the order of 400 square km, about the size of New England and New York combined. The ecosystem models work on the basis of a grid size of 0.5° X 0.5° or 60km squared. Therefore the results that the GCMs reveal for their large scale grids must be interpolated down to the 0.5 X 0.5 grid size.

The IPCC indicates that the GCMs are "generally realistic on large scales" reproducing features such as tropical convergence zones, mid latitude depression belts, and the El Nino Southern Oscillation. "However on regional scales (2,000 km or less), there are significant errors" (Houghton et al. 1990).

As the regional ecosystem models are based upon information at this smaller grid size we must be cognizant of these "significant errors" and try to convey them in some way.

4.3. Neglecting Uncertainty: Best Guesses, Business as Usual, and Base Cases

In an effort to "inform the necessary scientific, political, and economic debates and negotiations that can be expected" on the issue of climate change, the World Meteorological Organization and the United Nations Environmental Programme established the Intergovernmental Panel on Climate Change (IPCC) a body of several hundred scientists from 25 countries to prepare, review, and report findings in the arena of climate change. The IPCC was divided into three working groups. Working group one focused on scientific assessment. Working group two focused upon environmental and socioeconomic impacts of climate change. Working group three was concerned with formulating response strategies (Houghton 1990). To both facilitate the communication and express their findings these working groups relied on numerical forecasts.

For example, in order to communicate with each other, the working groups required a common set of emissions forecasts. Likewise, policy makers required estimates of changes in temperature, precipitation, and sea level rise in order to communicate with each other and with the public.
Although modelers, scientists, and policy makers involved in the process did not feel comfortable with presenting specific forecasts, the final result of the process

was the use of "best estimates", "business as usual" and "base case" which were essentially treated as forecasts. For example, increased concentrations of GHGs were projected to cause an increase of 0.3°C rise in temperature per decade with an uncertainty range of 0.2°C to 0.5°C. This correlated to a "best estimate" of 2.5°C by the end of the next century. Likewise, a "business as usual" emissions scenario was forecast to cause a 2XCO2 equivalent increase in GHGs by 2030.

The procedure in arriving at these numbers was sometimes arbitrary. Take for example the choice of the years 2030, 2060, and 2090 used by the working groups as the 2XCO2 dates as described by one of the participants in the process:

> People said there should be a business as usual scenario, and that would mean that CO2 would double around 2050, and then somebody else said, yeah but when you look at all the other gases it would happen sooner, and so they said well O.K., let's bracket 2060. And we ended up with 2030 and 2090. Then primarily because the Dutch pushed for it at a subsequent meeting, with some other countries, they said we should have at least one scenario that stabilizes well below a doubling. And so the fourth scenario was added. (From Margolis, 1992).

Such numbers were subject to a great deal of uncertainty and disagreement. However, once put forward they were often accepted by policy makers with an artificially high degree of confidence.

These "best estimates" are often used by those who study the effects of climate change despite any level of uncertainty. For example, Cline (1992) utilizes the IPCC best estimates of temperature and precipitation changes to attain estimates of economic impacts of global warming. Additionally, when policy makers attempt to analyze the effects of implementing various policies such as carbon taxes they often concentrate solely on the "best guess" scenario. To simply concentrate on these "best guess" or "business as usual" scenarios can

be dangerous. The appropriate strategy would be to recognize the uncertainty and incorporate it into both analysis and policy.

4.4. Dealing with Uncertainty

One area where uncertainty has been addressed rather successfully is in energy modeling. Energy models use input variables such as population growth, energy conservation, and elasticities of substitution to project future energy use and CO2 emissions. Two types of analysis can be used with these models. The first is scenario analysis. Here the modeler selects the value of each variable that is input into the model. The second type of analysis is probabilistic analysis where the modeler selects a range of possible parameters as input so that many scenarios can be simulated.

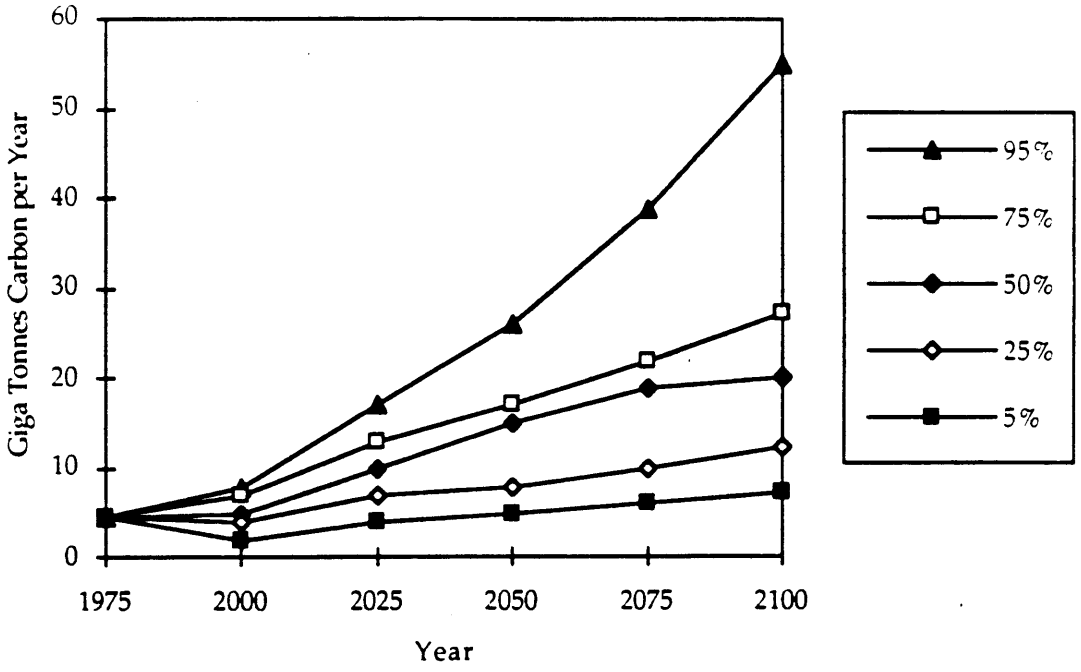
The benefit of probabilistic analysis is in its capacity to focus on the uncertainty of the input assumptions. This approach has been used by, Nordhaus and Yohe (1983), Edmonds et al. (1984, 1986) and Richels and Manne (1993). We will briefly discuss their work below.

The technique these researchers used is termed Monte-Carlo sampling. With this technique the modeler assigns a range of probabilities to each input variable. A computer program is then used to randomly select values of these parameters based upon their relative probabilities.

Nordhaus and Yohe assigned a range of probabilities to 10 key parameters used as input in their energy-emissions model. Using these parameters, a range of possible futures was projected shown in figure 4.1. The results indicate, not only possible outcomes, but the relative probabilities of these outcomes. For example in the absence of policy intervention, there is a 5% chance that in the year 2050 carbon emissions will be below 5GtC/yr., a 25% chance that emissions

will be below 8 GtC/yr and a 50% chance that carbon emissions will be below 15 GtC/yr, etc..

Figure 4.1. Probabilistic Analysis Projections of the Nordhaus and Yohe model (from Margolis 1992)

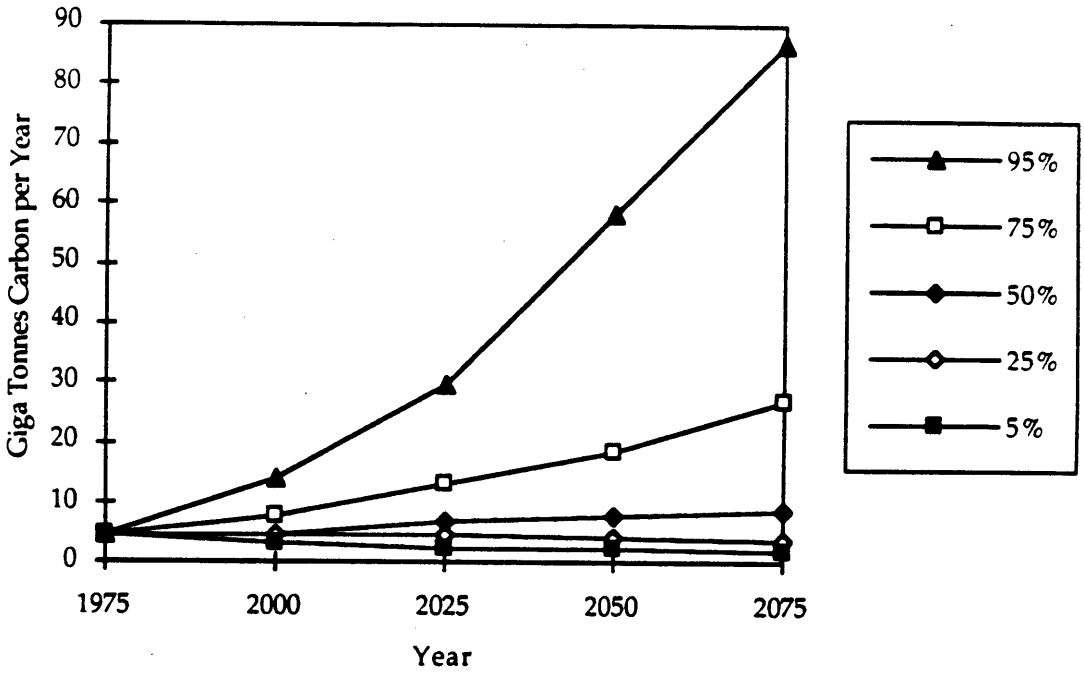


Edmonds et al. utilized this approach with the Edmonds-Reilly model. They assigned uncertainty ranges to 79 input variables to produce results shown in figure 4.2

A recent study by Manne and Richels (1993) uses an approach similar to that of Nordhaus and Yohe and Edmonds et al.. Here, probability values are assigned to each of the input variables however. However, these probabilities are not determined by the authors. Instead the authors poll "experts" to determine the probability values. Manne and Richels suggest that the numbers are still subjective but perhaps more rigorous than those that they themselves

would have derived as they are based upon the opinion of people who are knowledgeable in their various fields.

Figure 4.2. Probabilistic Analysis Projections of the Edmonds/Reilly Model (from Margolis 1992)



Margolis (1992) used the Edmonds-Reilly model to build upon the work of Edmonds et al. and Nordhaus and Yohe to present a probabilistic policy approach. Margolis selected five input variables to generate 100 equally probable scenarios of CO2 emissions. He then explored how policies such as a carbon tax would effect the range of possible outcomes. The intent was that "we really

ought to be concerned [with] how a particular set of policies will effect the distribution of possible futures instead of how they will effect a specific future."

4.5. Incorporating Uncertainty into Ecosystem Modeling

The advantage of the approaches illustrated above are that they can (1) provide policy makers with a range of possible outcomes and present their relative likelihood's and (2) provide a tool to determine the relative sensitivity of outcomes to certain inputs variables. Such capabilities are extremely important when dealing with a problem with the magnitude and uncertainty of climate change. One could envision the use of these strategies in various aspects of climate change analysis (agricultural modeling, for example). Central to the above approaches is the necessity of generating hundreds of runs for analysis and comparison.

Current approaches to ecosystem modeling which center upon the production of ecosystem maps do not lend themselves to the above techniques because it would require comparison of hundreds of maps. This points to the need to develop summary measures to interpret the content of these maps.

It is particularly difficult to incorporate uncertainty into the regional vegetation models. The Holdridge Life Zone model can serve as an example. The Holdridge system predicts vegetation distribution based upon inputs of temperature and precipitation. These values are obtained from GCMs. In order to get a range of outputs, modelers may use data from many GCM runs. However the values used are mean values. The range of uncertainty can not be incorporated into the vegetation maps. One could envision producing a multitude of vegetation maps based upon the range of possible GCM outputs. However, such a task would be cumbersome and of questionable value.

In the next chapter we present several different summary measures of life zone change. We will offer two ways in which to measure the possible impacts of climate change on ecosystems, one in terms of biomass, the other in terms of "life-zone displacement." The intention is that if we can determine which factors of ecosystem change are important, and separately quantify these factors, then we can perhaps utilize the techniques described above to incorporate uncertainty into ecosystem change analysis.

Chapter 5

Quantification Functions:

Biomass and Ecosystem Change

5.1. Background

Chapter three illustrated the results that regional ecosystem models can generate. These results can be reviewed by visually comparing vegetation maps and looking at various tables which indicate which type of ecosystem zone has moved to another type of ecosystem zone. Maps are useful way of getting a general impression of the way in which ecosystems may change in response to changing climate. However, what do maps tell us about changes in ecosystems that are of value or importance? For example, will the future planet have a greater capacity to maintain biodiversity? Will it act as a net source or sink of carbon? Will it have a greater capacity to produce agricultural staples? More generally, can we expect that the effects of climate change will have little impact on the overall characteristics of ecosystems or will the nature of the biosphere change to a great degree? Currently vegetation maps are the primary tool we have to address these questions at the global level. The goal of this chapter is to lay the ground work for seeking an alternative way of interpreting the meaning of the ecosystem change aside from visual comparison of maps.

Quantification factors will be introduced and discussed in the areas of biomass and "life-zone displacement" by utilizing the Holdridge Life Zone Classification System. Selected factors will then be applied to a change from a current simulated climate to perturbed climate scenarios of 2XCO2 equivalent atmospheres.

5.2. Biomass

Olson et al. (1983) provide a carbon index which can be used to correlate life-zone type with biomass[3]. For our analysis the 39 Holdridge Life Zones were aggregated into 14 different biome types. Table 5.1 shows these biome types and their relative values of carbon storage.

Table 5.1. Carbon Storage Values by biome type

	Soil Carbon * Mean kg/m^2	Live Vegetation † Mean kg/m^2	Total Carbon Storage Mean kg/m^2
Tundra Moist Tundra Wet Tundra Rain Tundra	14.3	5.0	19.3
Cool Forest Dry Tundra Boreal Desert Boreal Dry Scrub	10.2	2.0	12.2
Boreal Forest Boreal Moist Forest Boreal Wet Forest Boreal Rain Forest	15.7	10.0	25.7
Cool Temperate Forest Cool Temperate Moist Forest Cool Temperate Wet Forest Cool Temperate Rain Forest	12.9	12.0	24.9
Warm Temperate Forest Warm Temperate Moist Forest Warm Temperate Wet Forest Warm Temperate Rain Forest	10.6	11.0	21.6
Cool Desert Cool Temperate Desert Cool Temperate Desert Scrub	9.9	0.6	10.5
Steppe Cool Temperate Steppe	13.3	3.9	17.2

[3]The authors provide an index of soil carbon per life-zone from which values were taken directly. There is not a similar index for vegetation carbon storage. Vegetation carbon content was derived by estimating "natural" vegetation distribution based upon the terrestrial vegetation map provided by Olson et al. (1983) (which shows both natural and altered vegetation complexes) and using the values that the authors provide for carbon content of these vegetation complexes.

Savanna Subtropical Thorn Woodland Tropical Thorn Woodland Tropical Very Dry Forest	5.0	5.0	10.0
Hot Desert Warm Temperate Desert Warm Temperate Desert Scrub Subtropical Desert Subtropical Desert Scrub Tropical Desert Tropical Desert Scrub	2.7	0.4	3.1
Chaparral Warm Temperate Thorn Steppe Warm Temperate Dry Forest	8.0	4.0	12.0
Dry Tropical Forest Subtropical Dry forest Tropical Dry Forest	10.5	7.0	17.5
Subtropical Forest Subtropical Moist Forest	9.2	12.0	21.2
Tropical Rain Forest Subtropical Wet Forest Subtropical Rain Forest Tropical Moist Forest Tropical Wet Forest Tropical Rain Forest	11.4	16.0	27.4

*From Olson et al. 1983
†Estimated by author based on Olson et al. (1983) ecosystem map

Our approach here is not novel. Several authors have interpreted the effects of life-zone change on terrestrial carbon storage. Our numbers differ from those of previous authors because of different estimates of carbon storage for live vegetation (Smith 1993).

The IIASA database (1990) of temperature and precipitation was used to simulate current global vegetation distribution based on the Holdridge Life Zone Classification System (Holdridge 1947). Data for the perturbed climate was taken from the following GCMs: Godard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), Oregon State University Institute for Atmospheric Physics (OSU), and the United Kingdom Meteorological Office (UKMO). Applying the Holdridge Classification system to

these data sets produces vegetation maps shown in figure 3.2 (a-e). The change in global mean temperature for each of these models is given in table 5.2.

An index for the amount of global biomass is then simply the product of the biomass value per life-zone and total life-zone area and the estimated change can be determined by comparing the totals under current and 2XCO2 climate. Results of model runs to determine changes in North America and globally are show in table 5.3. (See appendix A for computer code.)

There is a decline in tundra in all four scenarios primarily from the shift of tundra to forest. This is due to increases in temperatures in the high latitudes and the subsequent migration of boreal forests. Additionally, polar desert is seen to decline as tundra moves northward to take its place. All four scenarios see a large percentage increase in tropical rain forest and dry tropical forest. All show an increase in hot desert except for UKMO which shows a decrease. Aside from these general trends the results of the models vary significantly.

At first glance it seems odd that there is not a correlation between the relative severity of the GCM projections as demonstrated in both the maps (figure 5.1) and the mean estimates for changes in precipitation and temperature (table 5.1) when compared with the changes in carbon storage. This is due to the different impacts that the models project at the regional level.

Superficial examination of the values for total change in carbon storage among the different scenarios might lead one to believe that because one GCM indicates that there will be a loss in carbon storage and another shows a gain, that on aggregate the result is a wash. Such an assessment might be closer to the truth if each model showed the same trends of life zone change across the board but simply differed slightly in the magnitude of their projections. A look at the details however reveals that this is not the case. The models show agreement in some areas but disagreement in many others.

Table 5.2. General Circulation Models Used to Construct Climate Change Scenarios. Mean projections of Temperature and Precipitation are shown (from Smith et. al. 1992)

GCM	Resolution (lat/lon)	Change in mean global:	
		Temperature (°C)	Precipitation (%)
[1]Oregon State University (OSU)	4 × 5°	2.84	7.8
[2]Geophysical Fluid Dynamics Laboratory (GFDL)	4.5 × 7.5°	4.00	8.7
[3]Goddard Institute for Space Studies (GISS)	7.8 × 10°	4.20	11.0
[4]United Kingdom Meteorological Office (UKMO)	5 × 7.5°	5.20	15.0

Table 5.3. Changes in carbon storage (kg) for four climate scenarios and current climate for a) the globe, and b) North America by biome type; and c) global aggregate, and d) North America aggregate

a) Global	Unit Storage	Total Current	Changes in Storage Under 2XCO2 ($kg \times 10^9$)			
Biome Type	kg/m2	$kg \times 10^7$	OSU	GISS	GFDL	UKMO
Ice and Polar Desert	0.0	0.0	0.0	0.0	0.0	0.0
Tundra	19.3	17.2	-5.7	-5.9	-9.7	-10.6
Cool Forest	12.2	3.4	0.0	-0.4	0.2	-1.2
Boreal Forest	25.7	38.6	-2.5	-4.1	-14.2	-12.5
Cool Temperate Forest	24.9	24.7	3.3	7.9	3.7	6.6
Warm Temperate Forest	21.6	6.9	-1.9	-3.0	-2.8	-1.0
Cool Desert	10.5	4.2	-0.8	-1.7	-0.8	-1.9
Steppe	17.2	12.7	2.6	-0.3	-7.3	-0.1
Savanna	10.0	9.6	2.6	7.1	4.4	7.1
Hot Desert	3.1	6.0	-0.7	-1.3	-0.3	-0.8
Chaparral	12.0	6.7	-0.7	-0.1	2.3	3.7
Dry Tropical Forest	17.5	26.0	0.5	8.5	8.6	-20.3
Subtropical Forest	21.2	32.1	-10.5	-15.8	-11.0	-16.5
Tropical Rain Forest	27.4	27.2	33.3	26.4	20.5	16.1
		215.2	19.7	8.7	17.5	9.4

Table 5.3 (cont.) b) North America

Biome Type	Unit Storage kg/m2	Total Current Storage kg x 10^7	Changes in Storage Under 2XCO2 (kg x 10^9) OSU	GISS	GFDL	UKMO
Ice and Polar Desert	0.0	0.0	0.0	0.0	0.0	0.0
Tundra	19.3	3.8	-1.1	-0.7	-2.2	-2.2
Cool Forest	12.2	0.4	0	-0.2	-0.2	-0.2
Boreal Forest	25.7	10.6	-1.9	-2.4	-4.2	-4.2
Cool Temperate Forest	24.9	6.2	1.4	1.5	-0.1	-0.1
Warm Temperate Forest	21.6	1.9	-0.8	-1.2	-1.2	-1.2
Cool Desert	10.5	0.5	0	-0.2	-0.1	-0.1
Steppe	17.2	3.6	0.8	-0.1	2.0	2.0
Savanna	10.0	0.6	0.4	0.9	0.9	0.9
Hot Desert	3.1	0.2	0.1	0	0.1	0.1
Chaparral	12.0	1.2	0.1	0.5	1.7	1.7
Dry Tropical Forest	17.5	1.8	0.8	2.0	2.5	2.5
Subtropical Forest	21.2	2.6	0.6	0.1	-0.2	-0.2
Tropical Rain Forest	27.4	0.7	0.7	0.8	0.3	0.3
		34.2	1.1	0.8	-1.0	0.3

c) Global aggregate

Scenario	Total Carbon Storage	Change
Current	2.2152 X 109	
OSU	2.2348 X 109	9.1%
GFDL	2.2388 X 109	4.0%
GISS	2.2369 X 109	8.1%
UKMO	2.2463 X 109	4.2%

d) North America aggregate

Scenario	Total Carbon Storage	Change
Current	3.4186 X 10^8	
OSU	3.5295 X 10^8	3.2%
GFDL	3.3190 X 10^8	-2.9%
GISS	3.5045 X 10^8	2.5%
UKMO	3.4496 X 10^8	0.9%

This great discrepancy in the projections of these models is important for two reasons. First, it highlights the danger of looking at the aggregate output. Second, it underlines the need for a mechanism to illustrate such a range of discrepancies.

Here we have used the biomass calculation to determine the range of outputs between the four different models. One could envision applying this

calculation to a multitude of runs from a single climate model, using Monte-Carlo sampling of input parameters with defined levels of uncertainty. By using such an approach we could project a range of possible biomass change projections along with their relative probabilities.

5.3. Life-Zone Change

5.3.1. Measuring Life-Zone Change in Terms of Societal Welfare

There are various ways to think about environmental change by utilizing the Holdridge Life Zone Classification System. One is to take the equilibrium model as valid and assume for a moment that all species will migrate with change and appear just as they do today only in their new designated regions. If we make this assumption then we can ask the question of whether this new distribution is more or less favorable to society. Is the new ecosystem distribution "better" or "worse" than our current ecosystem distribution. One way to determine the answer to this question is to assume that society has a unique and consistent value for each specific ecosystem. If this were the case, the value of a movement from one life-zone to another could easily be calculated. For example, if Boreal Evergreen Forest has a societal value of 10 and Boreal Scrub has a societal value of 5, a move from Boreal Evergreen to Boreal Scrub would yield a societal loss in value of 5 units. We could then value aggregate change as:

$$V(0 \rightarrow 1) = \sum_{i=1}^{n} C_i X_i^1 - \sum_{i=1}^{n} C_i X_i^0 \qquad (1)$$

where i = Holdridge type, C_i = is the unit value of ecosystem per hectare, X_i = quantity (i.e. number of hectares), n = number of Life Zones. Here V(0 -> 1) is used to indicate the value of change from the initial state 0 to the new state 1. Superscripts indicate the state.

A second way to think of Life Zone change is that there is no inherent value to each ecosystem but that some characteristic of the ecosystem has a value, such as its biomass content. In this case:

$$V(0\text{-}>1) = C[\sum_{i=1}^{n} b_i X_i^1 - \sum_{i=1}^{n} b_i X_i^0] \qquad (2)$$

where b_i is the quantity of biomass in each ecosystem. For example this would place a high weight on tropical rain forests and a low weight on deserts

Alternatively quantification could focus on the value of the change itself. This could be characterized as:

$$v(0\text{->}1)_1 = 0 \text{ if } i = j \text{ for } X_i^0, X_j^1 \qquad (3)$$

and

$$v(0\text{->}1)_2 = C \text{ if } i \neq j \text{ for } X_i^0, X_j^1 \qquad (4)$$

Here v is the unit value of change and C is the same for any movement from any X_i to any X_j; that is, the important thing is that a change has occurred, the type of change that has occurred is not important. The aggregate value for change is then:

$$V = N_1 v_1 + N_2 v_2 \qquad (5)$$

where N_1 is the total number of units that did not change and N_2 is the number that changed.

A more complex situation arises when the value of the change at any region is dependent on the nature of the life zone to which that region will change. In this case:

$$v(0 \rightarrow 1) = 0 \text{ if } i=j \text{ for } X_i^0, X_j^1 \quad (6)$$

and

$$v(0 \rightarrow 1) = C_{ij} \text{ if } i \neq j \text{ for } X_i^0, X_j^1 \quad (7)$$

Here we can visualize a transition matrix where the values of each C_{ij} (the value of the movement between life zone type i and life zone type j) can be determined. If it was indeed possible to know all C_{ij} then the sum of all C_{ij} multiplied by the number of movements would be the aggregate value. Here there are n^2 individual values of C_{ij}. Again, where n = the number of life zones.

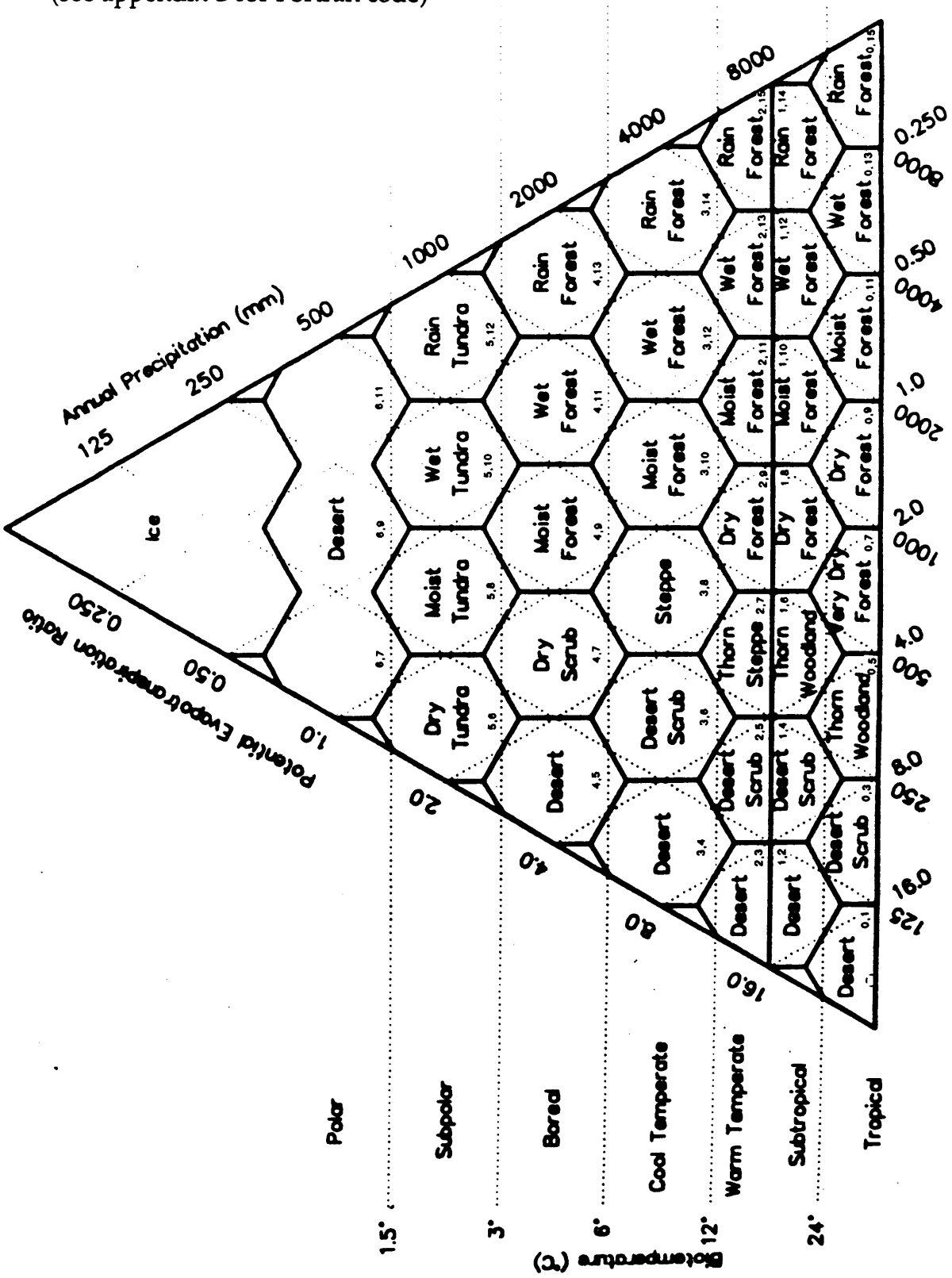
A final alternative that we propose and will apply to climate models for comparison and discussion takes an intermediate approach. That is that the magnitude of the value of change is related to the actual magnitude of change, i. e., how different a new life zone is from the original. We assume that the value of a change from one zone to another is related to the degree of change that takes place. Here the Holdridge diagram could be thought of as a two dimensional grid with each life-zone representing an (x,y) coordinate in "Holdridge Space" (figure 5.2). If a region changes from one life zone to another then the value of that change would be related to the distance traveled in "Holdridge space." This change could be defined as:

$$\sqrt{(x_2-x_1)^2 + (y_2-y_1)^2} = d \quad (8)$$

Where x_1,y_1 represents the position in Holdridge space of the original life zone and x_2,y_2 represents the position in Holdridge space of the new life zone. d represents the value of "life zone displacement."

Such a treatment offers a way to numerically compare different climate change scenarios or the relative effects of climate change on different regions.

Figure 5.1. Holdridge Life Zone with coordinates. The coordinates were chosen so that a movement from one zone to an adjacent zone along its axis would be represented by a value of 1. This is accomplished by dividing equation (8) by $\sqrt{2}$ (see appendix B for Fortran code)



The values of environmental change could then be summed to yield an aggregate value of environmental change for each perturbed climate run or for comparison of change between regions.

5.3.2. Life Zone Displacement as a Measure of Societal Welfare

One way to interpret the latter approach is to assume that the further one moves in Holdridge space away from the original life-zone, the larger the cost. Such reasoning is not completely arbitrary. It could be assumed that people choose areas in which to live and work because they prefer that particular environment. If the environment changes with a changing climate this could very well be undesirable to the inhabitants and viewed as a negative consequence of climate change. Likewise, a greater change is even less desirable. It is reasonable to assume that people grow accustomed to the area in which they live and become fond of its unique qualities. They may prefer not to see it change.

A study that is intended to measure societal preference to such change is scheduled to soon be undertaken by the departments of Economics and Environmental Studies at Yale University (Mendhelson 1993).

There are a great many problems with such a point of view. The reasons that people choose to live in a specific area may have little or nothing to do with the physical environment. Their choice may have more to do with the relative access to schools, jobs, etc.. Additionally, change need not always be negative. For example, in a place like Botswana, where rain is of significant value (in fact the words for currency and rain are the same) a change to a life-zone with greater precipitation could certainly be positive (Smith 1993).

For our analysis we do not assign change a positive or negative value. Our intent is that change be seen as value neutral. Of course this is not possible. By assigning coordinates to the Holdridge life zone system we are imposing a certain relative value for varying degrees of change. We are assuming that change has the same value in any direction. The problem is that invariably there is implied valuation in any and all of the above strategies.

5.3.3. Life Zone Change as a Physical Stress to the Environment

Another way to view the life zone quantification strategy just described is in terms of the biosphere's capacity to tolerate change. This would be a physical measure rather than a measure of value. If under climate change, the regional conditions of an ecosystem are altered slightly, the ecosystem may incur some damage but for the most part be left intact. The boundaries between different ecosystems are always abrupt. The transitional zones between various ecosystems often contain species that are capable of surviving in either area. If the change is gradual, the species in these transitional zones will migrate with the rate of change and this ecosystem may migrate intact (although we will perhaps see the extinction of species as it is often the transition zones which maintain the greatest species diversity). If changing conditions are more rapid or severe, perhaps only certain members of the transitional community will survive. Only the most opportunistic species will migrate and the new ecosystem will look quite different from the original.

By utilizing the Holdridge system in this fashion we are treating each life zone as a discrete ecosystem, distinctly bounded by identifiable climatic parameters. This is, of course, not the case. Some transitions are gradual with the limits of individual species having little to do with the community as a

whole. An example of such an ecological "continuum" are the different communities of deciduous forests in Eastern North America. Other transition areas are distinct, where the influence a dominant species can alter the characteristics of an ecosystem in a matter of meters. An example of such an "ecotone" transition is that between broad-leaved and coniferous forests in Northern New England. The transitions between ecosystems from Polar Desert to Rain Forest follow a combination of continua and ecotones.

Despite its simplicity, on a global basis the Holdridge classification system does a fair job at approximating the distribution of world bioregions (Henderson-Sellers 1990). It is therefore not arbitrary to assume that the Holdridge system gives us an indication of the relative difficulty that a region may have in making a transition from one life-zone to another.

One of the distinguishing characteristics of the Holdridge diagram is that, as it is set on a logarithmic scale, it implies that a greater absolute change in temperature and precipitation toward the top and left side of the Holdridge diagram represents a more drastic change than the same absolute change on the lower and right side of the diagram.

As an example, consider two areas. Area A is a Tropical Thorn Woodland with an average biotemperature of 28° which receives 300mm of rain per year. Area B is a Tropical Rain Forest with an average biotemperature of 28° which receives 9,000 mm or rain per year. If under climate change, both areas show an increase in temperature of 2° and a decrease in precipitation of 200mm respectively, area A will need to undergo a great deal more change to take on the characteristics of the new life zone. Area B will see less relative change and perhaps will have less trouble adjusting to these new climatic conditions The life-zone displacement value will represent these relative difficulties in adjustment with a greater value of "d" (distance traveled in Holdridge space) for

area A then for area B. As the climatic parameters of B are still within the Tropical Rain Forest life zone, the value of "d" will be zero. The climatic parameters of A see a displacement of two life zones resulting in a "d" value of two.

5.3.5. Life-Zone Displacement as Displacement

The previous two sections described what the life zone displacement quantification factor could mean. However it must be taken for what it actually is. It is simply a numerical interpretation of vegetation maps which are extremely limited, which are in turn based upon climate forecasts which are highly uncertain.

As such, the quantification factor should only be used for comparison. As vegetation distribution is highly correlated to climatic variables and these maps simply translate these variables into vegetation distribution, it is most likely a strong indicator for comparing the relative impacts that various climate change scenarios could have on the global biosphere. Based upon uncertainty that is layered into the process of forecasting these scenarios, a more rigorous interpretation is not appropriate.

5.4. Application of Life-Zone Displacement Quantification.

The code for the Fortran program to determine the value of life-zone change is offered in appendix B. The results are presented below.

The life-zone change quantification factor was applied to the OSU, GISS, GFDL, and UKMO GCM projections of 2XCO2 conditions for both North America and the globe. The results are shown in table 5.4.

Table 5.4. Life zone displacement values as projected by the OSU, GISS, GFDL, UKMO general circulation models for; a) North America, b) the globe.

a) North America

GCM	life-zone displacement	% change relative to UKMO value
OSU	5680	63.4
GISS	5980	66.8
GFDL	8638	96.5
UKMO	8953	100.0

b)Global

GCM	life zone displacement	% change relative to UKMO value
OSU	38,837	72.5
GISS	44,031	82.1
GFDL	46,288	86.4
UKMO	53,605	100.0

These values correlate well with the trends in the severity of mean temperature and precipitation projections (table 5.2). Also, there is no discrepancy between the relative trends in North America and the globe. When trying to draw information from these values however, the need for a benchmark for comparison becomes clear. The UKMO projection was used as a reference to illustrate the relative differences between values. However, it would be helpful to have a value for comparison that could relay more information than just these differences.

As an example, let's treat the drought in the US midwest of the 1930s as a deviation from a mean value of temperature and precipitation for the region. We could then use this deviation to create a new Holdridge map of this area and derive a life zone displacement value to this change. We could then compare this value with those resulting from GCM model runs to give us an idea of the severity of the impact of climate change. Alternatively this we could derive the life zone displacement value for ice ages as another benchmark.

Here we have used the life zone displacement to numerically illustrate the relative differences in the vegetation projections between the four GCMs. In

future research it could be useful to use the displacement value to illustrate the range of magnitudes that a particular GCM would show for life-zone displacement. One could then envision a range of life-zone displacement values based upon a multitude of runs. Graphically, this range of displacements would resemble a bell shaped. From the results of such an exercise we could determine a range of outcomes with relative percentages of occurrence, as well as mean and modal values. Such a method provides a strategy to move beyond basing our interpretation of ecosystem change under global warming on just a few GCM projections.

Chapter Six

Moving Forward

6.1 Summary and Conclusions

In this thesis we explored various issues involved in quantifying ecosystem change. We have introduced quantification factors or indices which will facilitate discussion of ecosystem change in the forum of climate change policy. We utilized the Holdridge Life Zone Classification System to generate quantification factors of biomass and life-zone displacement in order to test the use of such indices as a way of quantifying ecosystem change. Application of these factors highlighted the differences between the projections of double CO2 atmospheres for the four climate models utilized and showed promise as a useful tool to incorporate uncertainty into future ecosystem change assessment.

The Holdridge model was used for the sake of simplicity. However as it is based upon only two parameters, temperature and precipitation, it is limited in its ability to model ecosystem distribution. Two models have recently been developed to better assess the effects of climate change on ecosystem distribution; the Biome model and the Mapped Atmosphere-Plant-Soil System (MAPSS). These models do a better job at predicting global vegetation patterns; both current patterns based on observation, and prehistoric patterns based upon the fossil record. They were introduced here as an illustration of what needs to be considered when modeling regional distributions of biomes.

Throughout this thesis we have emphasized the limitations of using the regional ecosystem models to asses the impacts of ecosystem change. As these are equilibrium models based upon correlation of existing vegetation complexes, they do not give us a precise picture of future biotic response to change.

However, they offer an indication of the magnitude and direction of ecosystem change, and quantification factors that build from these models offer a mechanism by which we can compare the differences in direction and magnitude between the various climate models or a multitude of runs from a single climate model.

It is worth re-emphasizing the importance that the rate of future change will have on the earth's Biota. Will species migrate fast enough to stay within their favored climatic parameters or will they lag behind and vanish? Species today face a very modified landscape. Many of the sites that we have set aside as preserves and parks are locked in by development and human populations. Additionally, the fact that the population base of these organisms has been greatly reduced over the past 100 years or so will further hinder species response to change.

It is difficult to quantify what impacts, such as species loss, will mean to society. We have not yet, probably never will, and perhaps may not even want to, put a dollar amount on biodiversity. Quantification measures such as the ones we introduced will help policy makers by giving them indices for comparison. However policy makers must not act simply on objective data which can be rationally entered into a cost-benefit analysis. Policy making must also involve subjective decisions based upon the inputs of experts such as economists, politicians, and scientists. Ecological scientists need to take a more active role in this debate, and the process must facilitate their involvement.

6.2. Recommendations for Future Research

There are several steps which could be taken from here in furthering our ability to quantify ecosystem change. One could envision using the Biome or

MAPSS models as the basis for quantification factors rather than the Holdridge system. The eco-climate zones of these models could be assigned to a coordinate system of climatic and physical parameters, much like our Holdridge coordinate grid. As one of the major improvements of these models is their incorporation of soil moisture, a possible first step would be to include soil type as another dimension in the creation of a vegetation- parameter grid.

Another step that could be taken is in the construction of benchmarks to which we could compare the life-zone displacement values generated from GCMs and ecological models. Possibilities would be to derive the life-zone displacement values for the US drought of the 1930s, the little ice age of the period between 1500- 1650, and the last glacial maximum of 18,000 years ago.

The 2-D model that is being developed by the Joint Program offers another area of future research. The probabilistic analysis approach discussed in Chapter Four could be applied to the assessment of ecosystem change impacts. Parameters that are used as input into the 2-D climate model; such as emissions forecasts, and equations used to describe climatic feedbacks, could be assigned ranges of uncertainty. Monte Carlo sampling could be utilized to generate a multitude of runs. Quantification factors could then be applied to these runs to display a range of possible outcomes of ecological impacts. This mechanism offers a way for policy makers to move beyond making decisions based upon "best guess" scenarios. Uncertainty could then be incorporated into the decision making process rather than paralyzing the policy makers by their inability to agree on the validity of each "best guess."

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```
c       Program to calculate Biomass
        real MISC, LAT, LONG, CALCVALUE, OPP, HOLDRIDGE1(14)
        real LAND1(14), RES, TOTALLAND, TOTALCOUNTER,
TOTALHOLDRIDGE
        integer NUMBER, Q
        integer BIOME1(39), COUNTER1(14), I, J, SIMPLE, A

c       Reset values

        Do I=1,39
        BIOME1(I) = 0
        End Do

        Do J=1,14
        HOLDRIDGE1(J) = 0.0
        End Do

        Do I=1,14
        COUNTER1(I)=0
        End Do

        Do I = 1,14
        LAND1(I) = 0.0
        End Do

c       RES is 0.5 because each data is by every 1/2 degree by 1/2 degree

        A=0
        RES= 0.5
        TOTALHOLDRIDGE=0.0

        OPEN (4, FILE = 'HOL_CURR.DAT', STATUS = 'OLD')

11      READ (4, *, END = 22) MISC, LAT, LONG, NUMBER
c       If data in North America
        IF (LONG.LE.(-70.0) .AND. LONG.GE.(-140.0) .AND. LAT.GE.(10.0) .AND.
LAT.LE.(70.0)) THEN
                BIOME1(NUMBER) = BIOME1(NUMBER) +1
                A=A+1
                Q = SIMPLE(NUMBER)
                COUNTER1(Q) = COUNTER1(Q) +1
                LAND1(Q) = LAND1(Q) + OPP(LAT, RES)
                END IF
        GO TO 11

22      CLOSE (4)

c       Totalcounter counts number of data points in N. America
        TOTALCOUNTER=0.0
        Do I = 1,14
        TOTALCOUNTER= TOTALCOUNTER + COUNTER1(I)
        End Do

c       Checks to see land is correct
```

```
      TOTALLAND=0.0
      Do I = 1,14
      TOTALLAND=TOTALLAND + LAND1(I)
      End Do

      DO 35 I=1,14
      HOLDRIDGE1(I) = CALCVALUE(LAND1(I), I)
      TOTALHOLDRIDGE = TOTALHOLDRIDGE + HOLDRIDGE1(I)
35    CONTINUE

c     Print out values
      WRITE (*,*) 'For North America Total Biomass'
      WRITE (*,*) 'Lat 10-70, Long 140-70'
      WRITE (*,*) 'CURR datafile'
      WRITE (*,*) '         I  counter1    holdridge1   land1 '
      Do I = 1,14
      WRITE (*,*) I, COUNTER1(I) , HOLDRIDGE1(I),  LAND1(I)
      End Do
      WRITE(*,*) 'A=',A
      Write(*,*) 'TOTALCOUNTER=',TOTALCOUNTER
      Write(*,*) 'TOTALLAND=',TOTALLAND
      Write(*,*) 'TOTALHOLDRIDGE=', TOTALHOLDRIDGE
      END

c     Function Calcvalue will calculate the total biomass for each biome
      REAL FUNCTION CALCVALUE(LAND, I)
            REAL LAND, BIOME(14)
            INTEGER I
            BIOME(1) = 0.0
            BIOME(2) = 19.3
            BIOME(3) = 12.2
            BIOME(4) = 25.7
            BIOME(5) = 24.9
            BIOME(6) = 21.6
            BIOME(7) = 10.5
            BIOME(8) = 17.2
            BIOME(9) = 10.0
            BIOME(10) = 3.1
            BIOME(11) = 12.0
            BIOME(12) = 17.5
            BIOME(13) = 21.2
            BIOME(14) = 27.4
            CALCVALUE = LAND * BIOME(I)
      END

c     Function OPP will calc the amount of land that each datapoint represents
c     Function from AREA.FOR
      REAL FUNCTION OPP (LAT, RES)
            REAL LAT, RES, F
            REAL CFW, PI
            DATA CFW, PI /40000, 3.141592654/
            RES=0.5
            F = LAT * PI / 180.0
            X = CFW * RES / 360.0
```

```
            OPP = X * X * COS(F)
      END

c     Changes each biome from one of 37 to one of 14
      INTEGER FUNCTION SIMPLE(NUMBER)
            INTEGER NUMBER
            IF (NUMBER.EQ.1 .OR. NUMBER.EQ.2) THEN
            SIMPLE = 1
            ELSE IF (NUMBER.EQ.4 .OR. NUMBER.EQ.5 .OR. NUMBER.EQ.6)
THEN
            SIMPLE = 2
            ELSE IF (NUMBER.EQ.3 .OR. NUMBER.EQ.7 .OR. NUMBER.EQ.8)
THEN
            SIMPLE= 3
            ELSE IF (NUMBER.EQ.9 .OR. NUMBER.EQ.10 .OR. NUMBER.EQ.11)
THEN
            SIMPLE = 4
            ELSE IF (NUMBER.EQ.15 .OR. NUMBER.EQ.16 .OR.
NUMBER.EQ.17) THEN
            SIMPLE = 5
            ELSE IF (NUMBER.EQ.22 .OR. NUMBER.EQ.23 .OR.
NUMBER.EQ.24) THEN
            SIMPLE = 6
            ELSE IF (NUMBER.EQ.12 .OR. NUMBER.EQ.13) THEN
            SIMPLE = 7
            ELSE IF (NUMBER.EQ.14) THEN
            SIMPLE = 8
            ELSE IF (NUMBER.EQ.27 .OR. NUMBER.EQ.34 .OR.
NUMBER.EQ.35) THEN
            SIMPLE = 9
            ELSE IF (NUMBER.EQ.18 .OR. NUMBER.EQ.19 .OR.
NUMBER.EQ.25) THEN
            SIMPLE = 10
            ELSE IF (NUMBER.EQ.26 .OR. NUMBER.EQ.31 .OR.
NUMBER.EQ.32) THEN
            SIMPLE = 10
            ELSE IF (NUMBER.EQ.20 .OR. NUMBER.EQ.21) THEN
            SIMPLE = 11
            ELSE IF (NUMBER.EQ.28 .OR. NUMBER.EQ.36) THEN
            SIMPLE = 12
            ELSE IF (NUMBER.EQ.29) THEN
            SIMPLE = 13
            ELSE IF (NUMBER.EQ.30 .OR. NUMBER.EQ.31 .OR.
NUMBER.EQ.37) THEN
            SIMPLE = 14
            ELSE
            SIMPLE = 14
            END IF
      END
```

Appendix B. Life Zone Displacement Calculation

```
c       Program to calculate life zone changes
        real MISC1, LAT1, LONG1
        real MISC2, LAT2, LONG2
        real VALUE1, VALUE2, VALUE3, STRESS
        integer NUMBER1, NUMBER2
        integer BIOME(37, 2), I, J

c       BIOME(#; 1= X coordinate, 2= Y coordinate)
c       biome values, Holdridge life zones

        BIOME(1,1) = 7
        BIOME(1,2) = 8
        BIOME(2,1) = 6
        BIOME(2,2) = 7

        BIOME(3,1) = 5
        BIOME(3,2) = 6
        BIOME(4,1) = 5
        BIOME(4,2) = 8
        BIOME(5,1) = 5
        BIOME(5,2) = 10
        BIOME(6,1) = 5
        BIOME(6,2) = 12
        BIOME(7,1) = 4
        BIOME(7,2) = 5
        BIOME(8,1) = 4
        BIOME(8,2) = 7
        BIOME(9,1) = 4
        BIOME(9,2) = 9
        BIOME(10,1) = 4
        BIOME(10,2) = 11
        BIOME(11,1) = 4
        BIOME(11,2) = 13
        BIOME(12,1) = 3
        BIOME(12,2) = 4
        BIOME(13,1) = 3
        BIOME(13,2) = 6
        BIOME(14,1) = 3
        BIOME(14,2) = 8
        BIOME(15,1) = 3
        BIOME(15,2) = 10
        BIOME(16,1) = 3
        BIOME(16,2) = 12
        BIOME(17,1) = 3
        BIOME(17,2) = 14
        BIOME(18,1) = 2
        BIOME(18,2) = 3
        BIOME(19,1) = 2
        BIOME(19,2) = 5
        BIOME(20,1) = 2
        BIOME(20,2) = 7
        BIOME(21,1) = 2
        BIOME(21,2) = 9
        BIOME(22,1) = 2
```

```
      BIOME(22,2) = 11
      BIOME(23,1) = 2
      BIOME(23,2) = 13
      BIOME(24,1) = 2
      BIOME(24,2) = 15
      BIOME(25,1) = 1
      BIOME(25,2) = 2
      BIOME(26,1) = 1
      BIOME(26,2) = 4
      BIOME(27,1) = 1
      BIOME(27,2) = 6
      BIOME(28,1) = 1
      BIOME(28,2) = 8
      BIOME(29,1) = 1
      BIOME(29,2) = 10
      BIOME(30,1) = 1
      BIOME(30,2) = 12
      BIOME(31,1) = 1
      BIOME(31,2) = 14
      BIOME(32,1) = 0
      BIOME(32,2) = 1
      BIOME(33,1) = 0
      BIOME(33,2) = 3
      BIOME(34,1) = 0
      BIOME(34,2) = 5
      BIOME(35,1) = 0
      BIOME(35,2) = 7
      BIOME(36,1) = 0
      BIOME(36,2) = 9
      BIOME(37,1) = 0
      BIOME(37,2) = 11
      BIOME(38,1) = 0
      BIOME(38,2) = 13
      BIOME(39,1) = 0
      BIOME(39,2) = 15

      STRESS=0

      OPEN (4, FILE = 'HOL_CURR.DAT', STATUS = 'OLD')
      OPEN (9, FILE = 'HOL_GISS.DAT', STATUS = 'OLD')

11    READ (4, *,  END = 22) MISC1, LAT1, LONG1, NUMBER1
      READ (9, *,  END = 22) MISC2, LAT2, LONG2, NUMBER2

      IF (LONG1.LE.(-70.0) .AND. LONG1.GE.(-140.0) .AND. LAT1.GE.(10.0)
.AND. LAT1.LE.(70.0)) THEN
c     Data value in North America
            IF (NUMBER1.NE.NUMBER2) THEN
c     Special cases if one of the biomes is Ice (=1) or Polar Desert(=2)
                  IF ((NUMBER1.EQ.2 .AND. NUMBER2.EQ.1) .OR.
(NUMBER2.EQ.2 .AND. NUMBER1.EQ.1)) THEN
                        BIOME(1,1) = 7
                        BIOME(1,2) = 8
                        BIOME(2,1) = 6
```

```
                    BIOME(2,2) = 9

                ELSE IF (NUMBER1.EQ.1) THEN
                    IF (NUMBER2.EQ.3 .OR. NUMBER2.EQ.4 .OR.
NUMBER2.EQ.7 .OR. NUMBER2.EQ.8 .OR. NUMBER2.EQ.12 .OR.
NUMBER2.EQ.13 .OR. NUMBER2.EQ.14 .OR. NUMBER2.EQ.18 .OR.
NUMBER2.EQ.19) THEN
                        IF (NUMBER2.EQ.20 .OR. NUMBER2.EQ.21
.OR. NUMBER2.EQ.25 .OR. NUMBER2.EQ.26 .OR. NUMBER2.EQ.27 .OR.
NUMBER2.EQ.28 .OR. NUMBER2.EQ.32 .OR. NUMBER2.EQ.33 .OR.
NUMBER2.EQ.34 .OR. NUMBER2.EQ.35 ) THEN
                            BIOME(1,1) = 7
                            BIOME(1,2) = 8
                            END IF
                    ELSE
                            BIOME(1,1) = 7
                            BIOME(1,2) = 10
                    END IF

                ELSE IF (NUMBER2.EQ.1) THEN
                    IF (NUMBER1.EQ.3 .OR. NUMBER1.EQ.4 .OR.
NUMBER1.EQ.7 .OR. NUMBER1.EQ.8 .OR. NUMBER1.EQ.12 .OR.
NUMBER1.EQ.13 .OR. NUMBER1.EQ.14 .OR. NUMBER1.EQ.18 .OR.
NUMBER1.EQ.19 ) THEN
                        IF (NUMBER1.EQ.20 .OR. NUMBER1.EQ.21
.OR. NUMBER1.EQ.25 .OR. NUMBER1.EQ.26 .OR. NUMBER1.EQ.27 .OR.
NUMBER1.EQ.28 .OR. NUMBER1.EQ.32 .OR. NUMBER1.EQ.33 .OR.
NUMBER1.EQ.34 .OR. NUMBER1.EQ.35 ) THEN
                            BIOME(1,1) = 7
                            BIOME(1,2) = 8
                            END IF
                    ELSE
                            BIOME(1,1) = 7
                            BIOME(1,2) = 10
                    END IF

                ELSE IF (NUMBER1.EQ.2) THEN
                    IF (NUMBER2.EQ.3 .OR. NUMBER2.EQ.4 .OR.
NUMBER2.EQ.7 .OR. NUMBER2.EQ.8 .OR. NUMBER2.EQ.12 .OR.
NUMBER2.EQ.13 .OR. NUMBER2.EQ.14 .OR. NUMBER2.EQ.18 .OR.
NUMBER2.EQ.19 ) THEN
                        IF (NUMBER2.EQ.20 .OR. NUMBER2.EQ.25
.OR. NUMBER2.EQ.26 .OR. NUMBER2.EQ.27 .OR. NUMBER2.EQ.28 .OR.
NUMBER2.EQ.32 .OR. NUMBER2.EQ.33 .OR. NUMBER2.EQ.34 .OR.
NUMBER2.EQ.35 ) THEN
                            BIOME(2,1) = 6
                            BIOME(2,2) = 7
                            END IF
                    ELSE IF (NUMBER2.EQ.9 .OR. NUMBER2.EQ.21 .OR.
NUMBER2.EQ.36) THEN
                            BIOME(2,1) = 6
                            BIOME(2,2) = 9
                    ELSE
                            BIOME(2,1) = 6
```

```
                        BIOME(2,2) = 11
                    END IF

                ELSE IF (NUMBER2.EQ.2) THEN
                    IF (NUMBER1.EQ.3 .OR. NUMBER1.EQ.4 .OR.
NUMBER1.EQ.7 .OR. NUMBER1.EQ.8 .OR. NUMBER1.EQ.12 .OR.
NUMBER1.EQ.13 .OR. NUMBER1.EQ.14 .OR. NUMBER1.EQ.18 .OR.
NUMBER1.EQ.19 ) THEN
                        IF (NUMBER1.EQ.20 .OR. NUMBER1.EQ.25
.OR. NUMBER1.EQ.26 .OR. NUMBER1.EQ.27 .OR. NUMBER1.EQ.28 .OR.
NUMBER1.EQ.32 .OR. NUMBER1.EQ.33 .OR. NUMBER1.EQ.34 .OR.
NUMBER1.EQ.35 ) THEN
                            BIOME(2,1) = 6
                            BIOME(2,2) = 7
                            END IF
                    ELSE IF (NUMBER1.EQ.9 .OR. NUMBER1.EQ.21 .OR.
NUMBER1.EQ.36) THEN
                        BIOME(2,1) = 6
                        BIOME(2,2) = 9
                    ELSE
                        BIOME(2,1) = 6
                        BIOME(2,2) = 11
                    END IF

                END IF

c       Calc life zone change

                VALUE1 = ( BIOME(NUMBER2, 1) - BIOME(NUMBER1, 1))
                VALUE2 = ( BIOME(NUMBER2, 2) - BIOME(NUMBER1, 2))
                VALUE3 = SQRT( VALUE1 ** 2 + VALUE2 ** 2) / SQRT(2.0)
                STRESS= STRESS + VALUE3
            END IF
        END IF

        GO TO 11

22      CLOSE (4)
        CLOSE (9)

c       Display values

        WRITE (*,*) 'For North America'
        WRITE (*,*) 'Lat 10-70, Long 140-70'
        WRITE (*,*) 'CURR vs GISS'
        Write (*,*) ' '
        WRITE (*,*) 'LIFE ZONE CHANGE', STRESS

        END
```